Challenges and Strategies for Increasing Adoption of Small Wind Turbines in Urban Areas

by

Kevin Ferrigno

S.B. Mechanical Engineering
Massachusetts Institute of Technology

Submitted to the System Design and Management Program in partial fulfillment of the requirements for the degree of

Master of Science in Engineering and Management

at the

Massachusetts Institute of Technology

May 2010
[June 2010]

Signature of Author: ______________________
System Design and Management Program
May 2010

Certified By: ______________________
Stephen R. Connors
Director, Analysis Group for Regional Energy Alternatives
Thesis Supervisor

Accepted By: ______________________
Pat Hale
Director, System Design and Management Program

Challenges and Strategies for Increasing Adoption of Small Wind Turbines in Urban Areas

by

Kevin Ferrigno

Submitted to the System Design and Management Program on May 14, 2010 in partial fulfillment of the requirements for the degree of Master of Science in Engineering and Management.

Abstract

A student group at MIT in cooperation with the MIT Department of Facilities is currently working to install a Skystream 3.7 wind turbine on MIT's campus. This has raised several questions about how to best develop small wind projects in urban environments. The best wind resources in the country exist in relatively remote locations and require large investments in electricity transmission infrastructure to be effectively utilized. In the meantime, several large and small projects have been developed in the Boston area. The urban environment presents many challenges to development including the interaction of urban buildings with wind flow, concerns from neighbors and government over the aesthetics and safety of turbines that are installed near human populations, environmental effects including wildlife, noise, and shadows. There are also many opportunities including the ability to use net metering, little or no transmission infrastructure costs, and the ability to build on existing wind resource data and project assessments to develop a large number of installations.

This document presents an overview of how the challenges of small wind turbine development in urban, suburban, and rural neighborhoods are currently being addressed by research in new and improved technology for turbines and siting, business strategies of existing companies, financing, and government policy. It looks at the strategy options available to businesses involved development of small wind turbines and evaluates the relative strengths and weaknesses of these strategies in a rapidly changing marketplace.

Thesis Supervisor: Stephen R. Connors
Title: Director, Analysis Group for Regional Energy Alternatives

Acknowledgements

I would like to thank the many classmates, faculty, staff, and others that have contributed to my work on this thesis and to my experience in the MIT System Design and Management Program.

To the many students I have met through the MIT Energy Club and interns at the US Department of Energy whose dedication to the energy industry helped motivate me in my own work.

To the members of the MIT Energy Club Wind Energy Sub-community, Renewable Energy Projects in Action, and Project Full Breeze. You provided the inspiration for my effort to examine the small wind turbine industry. Working with you on the MIT Wind Turbine Project has been an outstanding experience.

To Pat Hale and the rest of the SDM staff for continually improving the SDM program, making it an excellent example of how Engineering and Management education should be addressed, and assembling the outstanding cohorts I have had the pleasure of working with.

To Steve Connors, who provided encouragement, direction, feedback, and support through several potential thesis topics over the last 16 months.

To all of my colleagues in the SDM cohorts of 2008, 2009, and 2010, who shared their vast experience and knowledge in classes, hallway discussions, and the SDM January session.

To my wife Angie for her feedback, support, and motivation that she provided throughout my participation in the SDM program.

To my dad, whose support, encouragement, and guidance have been invaluable in helping me achieve my goals and set ever higher new ones.

Finally, I would like dedicate this thesis to the memory of my mother. She provided me with so much guidance over the years and I would never have been able to accomplish this without her years of support and guidance.

Table of Contents

List of Figures

List of Tables

Chapter 1: Introduction and Motivation

MIT has received the donation of a Skystream 3.7 wind turbine that is scheduled to be installed in 2010 on MIT's campus. The turbine will be installed in the middle of an urban landscape where it will be surrounded by tall buildings which will likely have significant impacts on the wind that the turbine uses to generate electricity. The MIT student center is topped with an array of solar panels, and proposals for other energy efficiency and renewable energy projects are ongoing or have been proposed for MIT's campus. While development of renewable energy, and specifically wind energy, in the US has grown at a rapid pace in recent years, most development has been in rural areas and development of wind power in cities and suburbs has seen only small growth. While growing the development of wind power in urban areas is challenging, this paper aims to determine if there are specific applications or conditions that lend themselves to faster rates of adoption of small wind turbines in urban areas.

In general, public attention and policy towards developing larger amounts of renewable energy sources has been increasing. There is growing concern over the human contributions to global climate change. In December 2009, the international meeting in Copenhagen to discuss international policy towards global climate change that is the latest political event bringing attention to this problem. In the US, electricity generation is responsible for 2.4 Billion Metric Tons of carbon dioxide emissions, or 41% of all carbon dioxide released into the atmosphere in the United States. (EIA 2009a) This has stimulated development of technologies that have low carbon dioxide emission footprints. In addition to issues around climate change, the US and other countries without sufficient domestic supplies of the fossil fuels to meet their energy demand face security risks associated with importing large quantities of fuel.

These concerns are encouraging the development of alternative energy sources which have no direct CO2 emissions and low lifecycle CO2 emissions. The primary technologies for electricity generation with low CO2 emissions are nuclear fission and renewable sources such as wind, solar, hydro, biomass, and geothermal energy sources.

When considering renewable energy for significant production of electricity, the cost and potential capacity are important factors in determining which renewable technologies can be implemented economically and on a large scale. Figure 1-1 shows costs comparisons for several electricity generation sources including both renewable and conventional generation sources. (Lazard 2008) Wind is among the most cost effective of the renewable options.

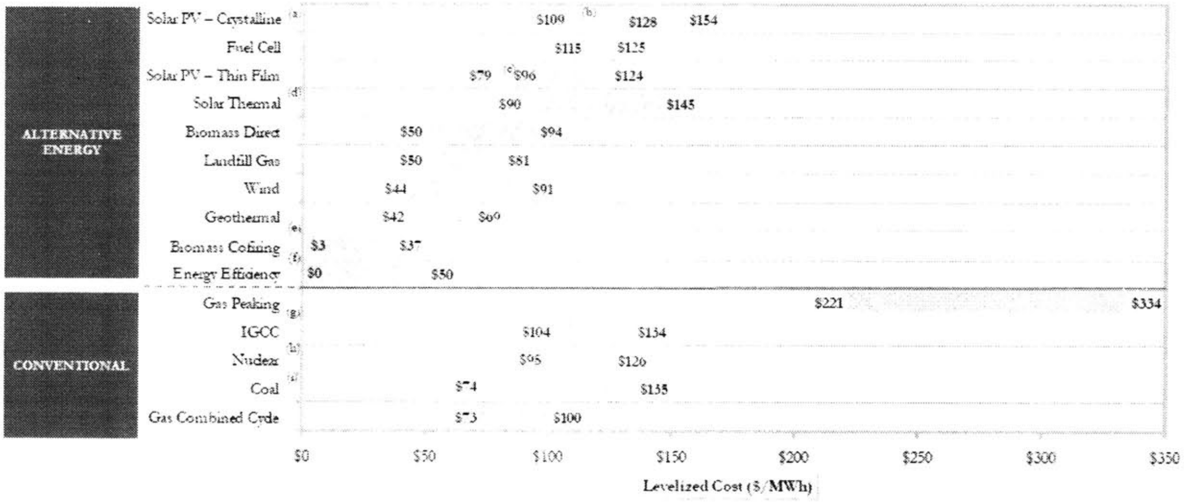
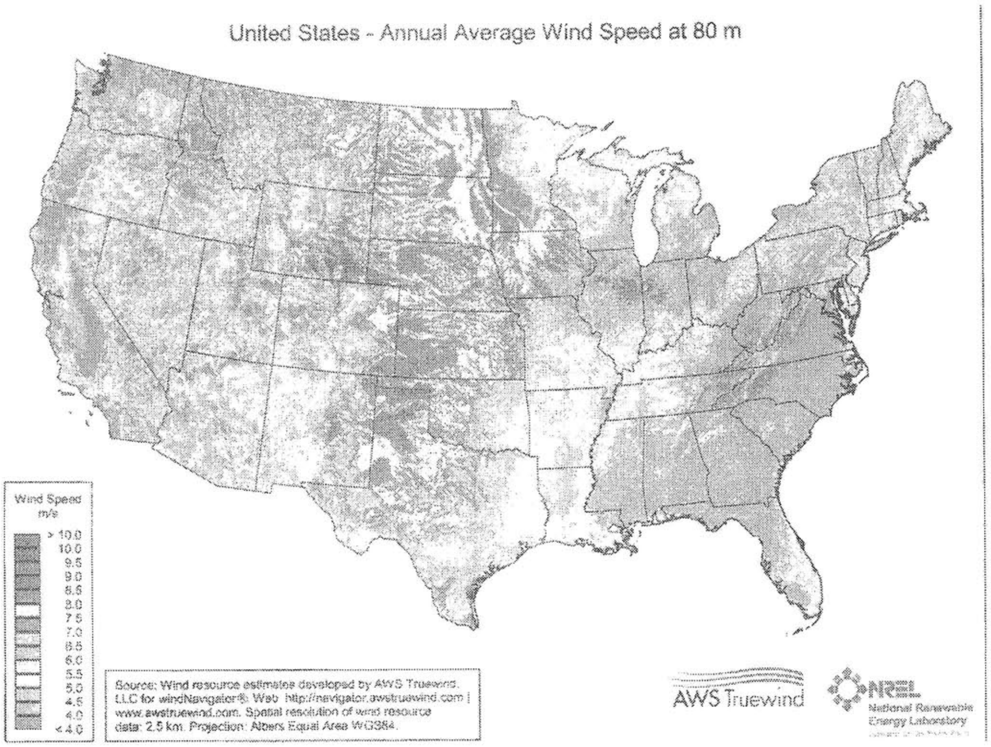


Figure 1-1: Estimates for levelized cost of energy (LCOE) for renewable and conventional generation sources after government incentives (Lazard 2008)

The availability of wind resources varies across different geographic regions. Figrue 1-2 is a map provided by NREL that illustrates the wind resource available across the United States. Figure 1-3 shows the population density of the United States by county. A quick comparison of the two figures shows that the best wind resources, and therefore the most economic wind generation, exist in different areas than the population. In order to achieve significant expansion of wind power in the United States, the Department of Energy estimates an investment in new electricity transmission infrastructure of over $15 Billion would be required. Assuming wind farms would be responsible for half of this cost, this would increase the capital costs of a new wind farm by an estimated 7%. (DOE 2008)

Because of the difficulties in developing large amounts of wind power in wind rich areas, there are opportunities to take advantage of the unique characteristics of urban areas to promote wind development. Urban wind projects do not need to rely on transmission and distribution infrastructure, so it will not require the same extensive investment in the electric grid infrastructure to develop. These projects can also take advantage of offsetting retail electricity use; the electricity generated can be valued at the retail electricity rate instead of the lower wholesale electricity rate. Further, there is increasing marketing power for individuals and businesses to appear green. Wind turbines are now a common element in advertising, even among companies with no presence in the energy industry. The presence of a wind turbine on one's property makes a statement about the owner's commitment to being environmentally responsible.



Source: Wind resource estimates developed by AWS Truewind, LLC for windNavigator® Web: http://navigator.awstruewind.com | www.awstruewind.com. Spatial resolution of wind resource data: 2.5 km. Projection: Albers Equal Area WGS84.

Figure 1-2: United States wind resource map (Wind Powering America 2010)

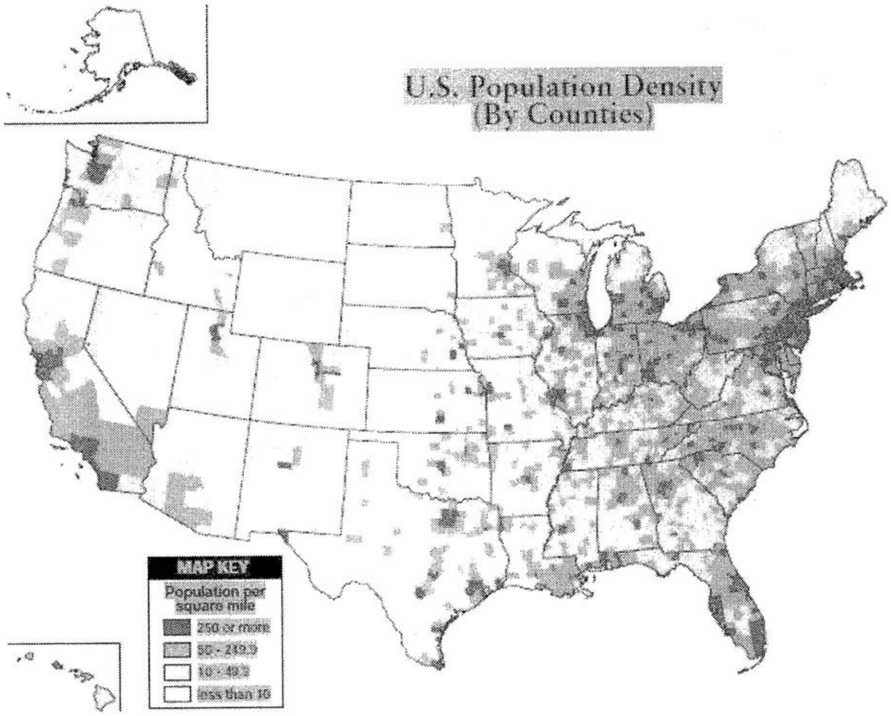


Figure 1-3: United States population density map (US Census Bureau 2009)

Urban wind power projects present difficulties in economies of scale. Large turbines on tall towers can produce electricity more cost effectively but are impractical in many locations. Even when practical, they may be met with local opposition to their environmental, aesthetic, and public safety impact. However, urban wind projects have the potential benefits of requiring no transmission investment and the potential to offset retail electricity use. This reduces the capital cost and increases the value of the electricity produced. It is still a challenge to identify projects where these benefits offset the economies of scale that make larger turbines competitive in the electric power industry.

Worldwide electricity generation in 2006 totaled just over 18,000 TWh with a total genearation capacity of 4 TW. World Capacity is expected to grow to 5.5 TW by 2020 and 6.5 TW by 2030. The US accounted for 4,100 TWh of electricity use and Europe 3,500 TWh of Electricity Use. The total electric generation capacity in the United States and Canada is about 1087 GW and capacity in Europe is 810 GW. (EIA 2009b) In the United States, wind capacity increased by 10 GW of installed power capacity in 2009 and increased the total installed wind capactity to 35 GW, or about 3 % of the overall capacity and results in wind generation of 2 % of electricity generation. (AWEA 2010) Worldwide, almost 40 GW of wind power was installed in 2009, and the total capacity worldwide is over 160 GW. (GWEC 201) Most of this capacity has been installed in rural areas in large wind farms.

AWEA has estimated the US market for small wind turbines to consist of about 13 Million US residences and about 835,000 commercial and public buildings. The estimated potential installed capacity from these markets is about 138 GW and AWEA has set a long term goal of 50 GW for installed small wind turbine capacity in the US. (AWEA 2005) This is slightly more than the current installed capacity of large wind turbines in the US and would represent about 3% of the total projected energy generation in 2020. While these numbers are optimistic and the market has not grown as rapidly as projected in 2005, the targets illustrate the potential of small wind to play a minor but significant role in the electricity generation mix.

The focus of this paper is to examine the potential for growth of small wind turbine installations in urban, suburban, and rural areas. Urban will be considered any area where the built environment puts specific constraints on turbine height, visibility, allowable noise, and impact of shadow flicker. These constraints limit the size of turbines that may be installed at many urban locations. This requires the analysis to consider smaller wind turbines or alternative turbine designs that can be installed where these constraints make the installation of larger turbines impractical. This will be accomplished by understanding what conditions are optimal for wind turbine development and what improvements in turbine cost, technology, business strategy, city planning, and regulatory policy are needed to realize the benefits that small wind turbines can provide. Specific applications where the value of electricity can be considered greater than the retail price will also be considered.

Chapter 2: Overview of the Wind Industry

Wind power has been in use for at least 2000 years, with various sources recording use as early as 200 B.C. Unusual applications have been recorded for wind energy including powering an organ and driving Buddhist prayer wheels. (Tester et al. 2005) However, its primary historic uses were to drive mechanical equipment—mainly to pump water and grind wheat. (Stankovic et al. 2009) Today, in industrialized nations where a large portion of energy needs are met through electricity use, wind is used primarily for electricity generation.

2.1 Characteristics of Wind Energy

The amount of energy in a mass wind can be calculated from the mass of the air and the wind speed. More practically, the power of the wind moving through a cross sectional area can be found from the air density and wind speed. The power in the air increases with the cube of increases in wind speed (Wizelius 2007, Stancovic et al. 2009, Gipe 2009):

$$\frac{P}{A} = \frac{1}{2}\rho v^3 \tag{2-1}$$

Where P is the power, A is the cross sectional area of the wind turbine, ρ is the density, and v is the wind speed. Thus, turbines with large cross sectional area in locations with high wind speed can produce the most power. But wind turbines sited in areas of high wind speeds are more important. If the wind speed doubles, the power content in that wind increases by eight times.

It is also important to note that because of the cube relationship between wind speed and power, the average wind speed at a single location may not be sufficient to characterize the energy potential of a wind turbine sited at that location. Sites with larger variation in wind speed may have more power potential than sites with less variation but the same average wind speed.

Wind speed measured at a particular location tends to follow a Wiebull probability distribution (Wizelius 2007, Stancovic et al. 2009). The Wiebull distribution is usually characterized by a scale parameter and a shape parameter. Alternatively, the distribution can be defined by its mean value and scale parameter. The Wiebull probability distribution has several properties that make it useful to model wind speeds. Most importantly, it has no possibility of negative values and has a long tail indicating low probability over a large range of high wind speeds. The shape of the distribution and tail is determined by the scale factor. However, since the power of the wind varies with the cube of the wind speed, the power that can be captured from the wind in the tail of the Wiebull distribution can be more significant. Two

Wiebull distributions with the same average wind speed but different shape parameters, k, are shown in Figure 2-1. Also shown is the relative total energy that can be captured over the distribution of wind speeds. Note the relative importance of the higher wind speeds in energy production of the blue distribution representing a shape factor of 2. The area under the blue dashed curve is much greater than that of the red dashed curve indicating that the energy potential in wind speeds following the blue distribution is greater than that under the red distribution.

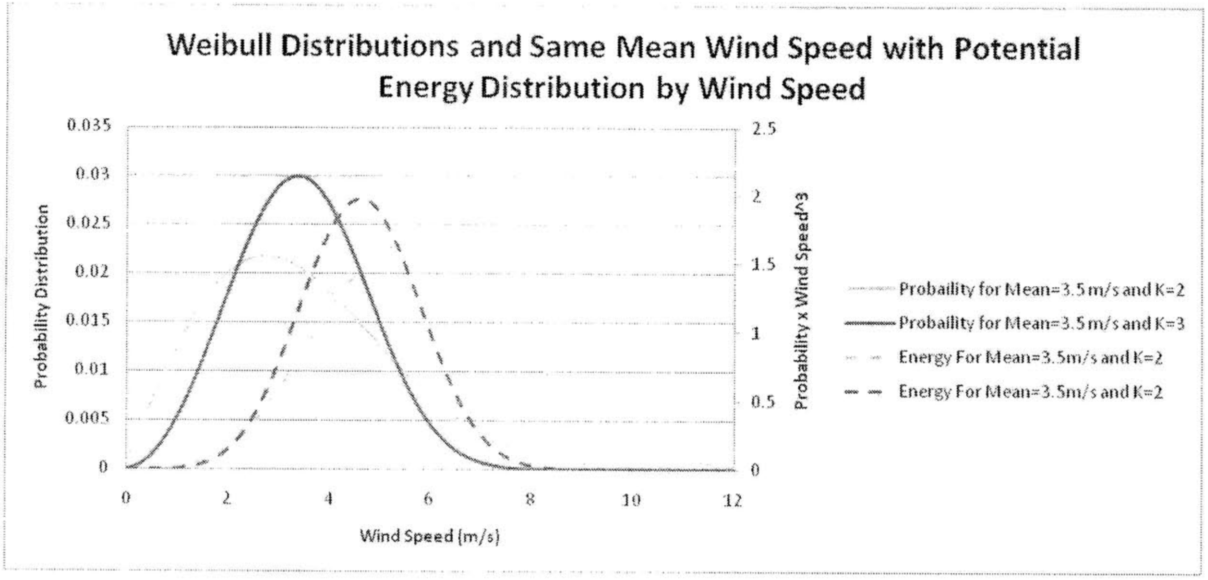


Figure 2-1: Wiebull distributions and energy output distribution

Wind speed also increases as height above ground increases (Wizelius 2007). Thus, a wind turbine placed on a taller tower will typically generate more energy than a turbine on a smaller tower at the same location. The rate of change of wind speed with height called the wind shear and knowing the wind speed at all heights at a location allow the generation of a wind profile. Placing turbines at higher altitudes to capture stronger winds must be balanced against the increased costs of taller tower heights. However, taller towers allow also allow larger rotors to be used and fewer turbines can produce the same output. (Khatri 2010) Estimates of tower costs for two different wind turbines are shown in Table 2-1. These costs show one aspect of the economies of scale of larger and taller turbines. Even if the cost/MW of the turbine itself does not scale well, increased output from being in higher and steadier wind coupled with savings in capital investment can greatly reduce the cost of energy generated from wind turbines.

Table 2-1: Tower costs increase for turbine size increase (Khatri 2010)

Turbine Size	**Tower Cost**	**Total Cost/MW**
1 MW	$350,000	$350,000/MW
4 MW	$500,000	$125,000/MW

The strength and pattern of wind speeds both in a single location and over large areas have a significant impact on the development of wind projects. Wind turbines operate best when the wind reaching the turbine blades is not affected by natural or manmade obstacles. These obstacles tend to slow the wind down and increase turbulence. Both of these changes to incoming wind reduce the potential performance of a wind turbine. The features found in urban areas have significant impact on the wind patterns in and around the built environment. Urban areas present additional challenges in siting wind turbine projects over rural wind farms. (Stancovic et al. 2009)

Of particular importance to urban wind installations, in addition to variations of wind speed with height, wind speed varies with the type of terrain over which the wind blows. Smooth surfaces such as the ocean or flat land with no vegetation or buildings produce the fastest wind speeds at the lowest elevations. As discussed previously, trees, buildings, and hills all disrupt wind flow, create wind shear, and decrease the wind speed at a particular location. Figure 2-2 shows this idea qualitatively by showing how wind speed changes with altitude over 3 different surfaces: flat water, a smooth plain, and a forest. These obstacles also create turbulence, which reduces the performance of wind turbine blades and increases the wear on turbine and it's supporting structure. In general, the best wind speeds exist above the tree canopy or building roofs in the area where the wind turbine will be placed. (Stankovic et al. 2007, AWEA 2010a) However, within an urban area, wind can be funneled around buildings creating locations below the rooftop levels where wind speeds might be better than above the rooftops.

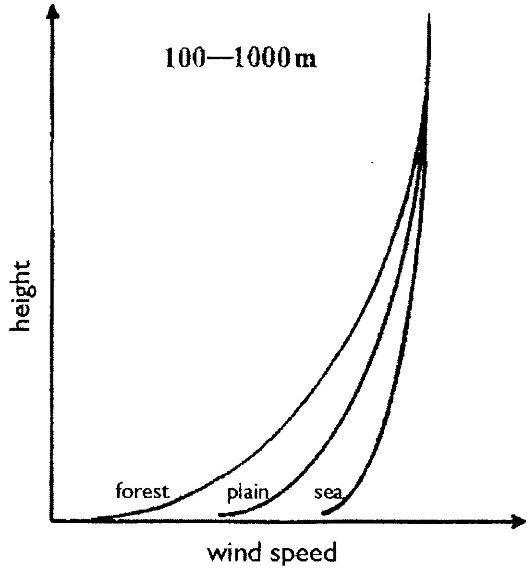


Figure 2-2: Wind speed as a function of height above different surface features (Wizelius 2007)

A wind turbine cannot extract all of the kinetic energy out of the wind, as this would require reducing the wind speed to 0. The maximum amount of energy that can be captured is known as the Betz limit. It is about 59%. (Wizelius2007)

While wind power is a clean source of energy, it is also an intermittent resource. Thus, the power generated from a wind turbine is dependent on the current conditions of the wind. When the wind is not blowing, power must be provided from other sources. When the wind is blowing, its speed often varies, such that other generation sources must adjust their output to compensate for changes in the wind.

2.2 Modern Wind Turbines

Wind turbines are available from as small as a few hundred watts up to a few Megawatts with at least one 10 MW wind turbine in development (SWAY 2010). Though no official standard for rating wind turbines exists, turbines are usually rated by their potential peak power output and this is referred to as nameplate capacity. This also roughly indicates the size of the turbine in terms of cross-sectional area, since most wind turbines are designed to achieve their rated power at around 13 m/s wind speed. Two wind turbines of the same rated nameplate capacity and similar efficiencies will likely have very similar cross-sectional areas and overall size.

A 1 MW turbine will typically have a maximum sustained power output of 1 MW. If it produced this output continuously for an entire year, it would produce 8760 MWh of energy. Specific installations are described by a capacity factor, which is the percentage of theoretical output a specific installation is expected to achieve over the long term. Thus, a 1 MW Turbine with a capacity factor of 30 % would be expected to produce 2628 MWh/year (8760 hours/year x 1 MW x 30%) on average. The capacity factor depends on both the characteristics of the turbine and the wind conditions for a specific installation. For a wind farm, capacity factor would also include the effects of upstream turbines on the performance of downstream turbines. It could also include reductions in capacity from routine maintenance or other service interruptions. Turbines are also described by their efficiency, which is the maximum percentage of wind energy that can be converted to electrical energy.

The wind turbine industry often groups the turbines into several categories. Large turbines are those with a nameplate capacity of over 1 MW. Medium Turbines are those from 100kW to 1MW. Small Turbines are those less than 100 kW. Some discussions of turbines also separate Micro Turbines, those under 10 kW, from small turbines. (Sharman 2010)

Wind turbines achieve significant economies of scale at their current sizes. Wizelius notes that increasing returns to scale is not an obvious property of wind turbines since weight of the turbine could be expected to increase by the cube of the turbine size, while it's swept area, the diameter of the turbine blades, would only increase by the square of the size. However, design optimization and increased height of the turbines has improved performance so that bigger turbines are still cost effective. (Wizelius 2007) The installed cost of large wind turbines in rural farms is typically $1500 to $2000 per Watt of capacity. For small wind turbines, the installed costs range from $3500 to $10,000 per Watt. (AWEA 2009)

2.3 Turbine Performance

A turbines performance can be stated as the maximum percent of total energy extracted by the turbine at its rated wind speed. This is known as the turbine's efficiency and is below the Betz limit of 59%. Commercially available turbines operate with maximum Cp values up to 45%. (Wizelius 2007) Figure 2-3 illustrates the typical efficiency of a turbine over a range of wind speeds.

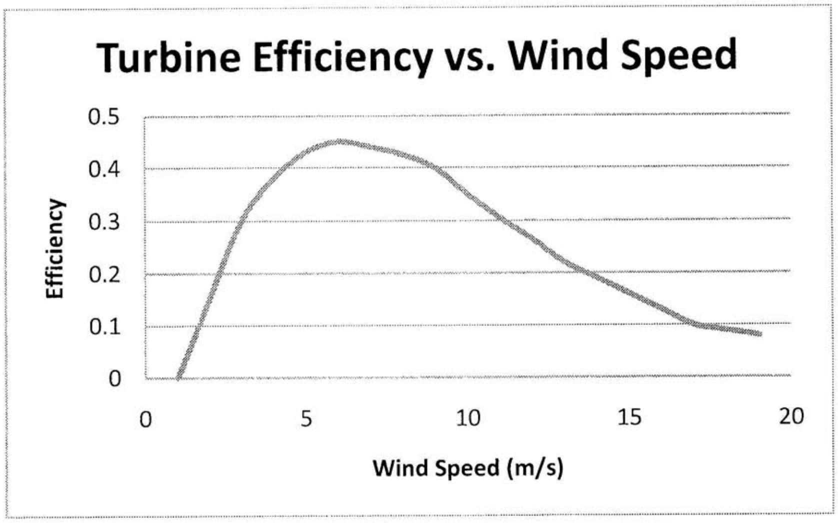


Figure 2-3: Wind turbine efficiency as a function of wind speed for a Siemens 1300 (Wizelius 2007)

Because efficiency varies with wind speed, wind turbine performance is represented by a power curve, which indicates the power output of the wind turbine as a function of the incoming wind speed. The power curve has several important characteristics, the cut-in speed, the rated speed, and the cut-out speed. The cut-in speed is the minimum wind speed at which the turbine produces power. The rated speed is the minimum wind speed where the turbine produces its rated output. The output power from the turbine rises gradually and the wind speed increases from the cut in speed to the rated speed. Above the rated speed, output power is limited to the rated power. (Wizelius 2007, Gipe 2009) The extra power in the wind because of the higher wind speeds is not able to be captured. Above the cut-out speed, the turbine stops for safety reasons and no power is produced at extremely high wind speeds. Turbines also have a survival wind speed, which is the maximum wind speed the turbine can withstand without being damaged. The power curve for the 2.4 KW Skystream 3.7 wind turbine is shown in Figure 2-4.

Design of a turbine to have an efficient power curve is important. There is a tradeoff between increasing the cost of the turbine in order to lower the cut-in speed or increase the turbine's rating and rated speed, both of which offer potential to increase the output of the turbine. Since turbines are installed at different locations with different wind speeds, the optimal design of the turbine must consider the range of wind profiles likely to be seen at different installations.

Most wind turbines installed today contain three blades connected to a central hub mounted on top of a tall tower. The potential efficiency of the turbine increases as more blades are used, but so does the cost of the turbine. The central hub connects through a gearbox to an electric generator, and power is converted from the generator's output to match the AC properties of the electric grid where it connects. The generator of a typical wind turbine operates asynchronously from the frequency of the electric grid, so power electronics are needed to condition the power from the wind turbine and send that power to the electric grid. These electronics also allow the turbine to meet other regulatory requirements required by grid operators.

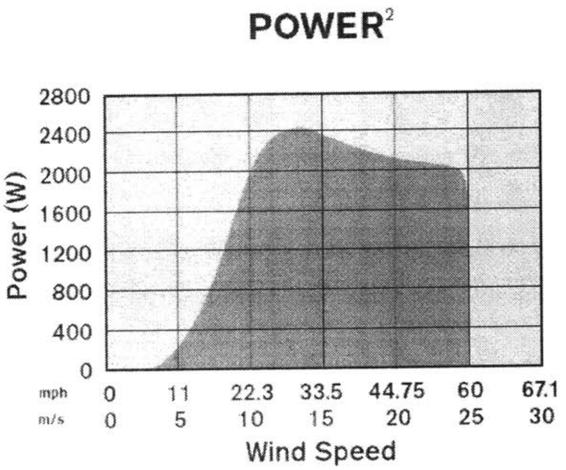


Figure 2-4: Power curve of Skystream 3.7 (Southwest 2010)

Large wind turbines utilize active control systems to control the orientation of the wind turbine to align it with changing wind directions. The pitch of the turbine blades is used to control the aerodynamics and the amount of power transferred from the wind to the rotor—to maximize the power transfer at low wind speeds, and to limit it to the safe operating range of the generator and electronics at high wind speeds. (Wright 2009)

2.4 Wind Farm Development

With the recent scale up in large wind turbine installations worldwide totaling 10's of GW in nameplate capacity per year and corresponding investments in the 10's of billions of dollars, the process of large wind turbine and wind farm development is well documented. A brief summary based on Wizelius' *Wind Project Development* follows.

The process of commercial wind farm development begins by identifying areas with high average wind speeds, and therefore large amounts of energy conversion potential. Wind resource maps such as those in figure 1-2 are readily available. More detailed maps are available from NREL that allow specific site selection. From the map, it is easily determined where the wind is strongest, and consequently, where a wind turbine can generate the most electricity. (Wizelius 2007)

When considering a site, however, the importance of transmission must also be considered. Transmission lines are not only a potential significant expense, but can take longer to site, permit, and build than generation resources. Once a suitable site is located and development rights obtained, several concurrent tasks are begun. First, detailed wind measurements at the site are obtained to verify with accuracy of the wind conditions at the site. Second, a detailed plan for developing the site is developed. Third, an environmental impact study is performed. Finally, an integration study on connecting the wind turbines to the power grid must also be done. (Wizelius 2007)

Wind Farms generally do a detailed measurement of the wind resource at a specific site which is used to demonstrate how much power will be generated. The power is usually sold via a Power Purchase Agreement (PPA) to a utility company. Once the amount of electricity to be generated and the purchase terms are determined, financing for the project will be finalized. Assuming that the environmental impact and permitting are completed, the wind farm can then be built. Building the wind farm involves building roads and other infrastructure for construction and maintenance equipment, building foundations for each turbine, erecting the towers, placing the nacelle (which contains the generator and control equipment) on the tower, and finally attaching the blades. (Wizelius 2007)The electrical infrastructure must also be installed, including connecting to the transmission grid.

For large wind farms, this review can take several years and cost in the hundreds of thousands of dollars. In some cases where opposition to development is higher, those costs can increase substantially. However, for most standard development cases, the capital cost of wind turbines is about $1.5 Million to $2 Million per MW of capacity, and the upfront assessment and review costs are relatively small for a large wind farm of 100 MW or more.

Chapter 3: A Screening Model for Small Wind Turbine Performance

3.1 Overview

A screening model for a small wind turbine is developed to help understand what cost and performance characteristics are required to make small wind turbines economically attractive in the applications discussed in Chapter 3. After the cost performance requirements are established, the value of technology improvements is evaluated in terms of meeting the required cost and performance characteristics.

The inputs to the model, along with the assumed baseline values, will be:

- Wind characteristics typical of application
  - Wiebull Distribution Mean Wind Speed, $v_{average}$, 5.5 m/s
  - Wiebull Distribution Shape factor, $k = 2$
- Turbine Performance characteristics
  - Turbine Efficiency, C_p
  - Peak Turbine Efficiency, $C_{pmax} = 35\%$
  - Cut In Speed, $v_{cut\text{-}in} = 3.5$ m/s (7.8 mph)
  - Rated Speed, $v_{rated} = 13$ m/s (29.1 mph)
  - Cut Out Wind Speed, $v_{cut\text{-}out} = 25$ m/s (56 mph)
  - Peak Efficiency Wind Speed, $v_{cpmax} = v_{cut\text{-}in} + 1$ m/s
- Turbine Capital Costs, C_O
- Operation and Maintneance Costs as a Percent of Capital Costs/Year, $a_{OM} = 3\%$
- Retail Price of Electricity, E_{cost}, \$0.04/kWh to \$0.20/kWh
- Annual Increase in Electricity Cost = 2%
- Discount Rate, $r_d = 10\%$
- Cost of Capital, $r_c = 7.8\%$
- Incentives, r_t, US Federal Tax Credit of 30%

From the model, we will be able to determine:

Target capital cost for a project that has 0 NPV. This will be referred to as the customer's willingness to pay for a wind turbine given a specific set of inputs. Reducing costs below the willingness to pay will result in a positive NPV and make wind turbine installations economically attractive to customers facing the specific wind conditions and turbine costs used.

Levelized Cost of Energy, LCOE. This measure is commonly used to compare the cost of different generation sources as in Figure 1-1. It is a secondary consideration here, our main goal is to identify capital cost limitations. If a project is to have positive NPV, it's levelized cost of electricity will fall below the avoided cost or sale price for electricity.

The willingness to pay helps determine which applications should be a higher priority market for turbine manufacturers. The LCOE is useful in determining comparisons to other forms of electricity generation, including rooftop solar and conventional electricity. The assumptions used for values made above are described in more detail when the model is explained.

The model will be separated into 2 parts. The first part will use the turbine performance characteristics to determine the turbine's capacity factor. The second part will use the turbine performance and economic parameters to either find the Net Present Value of a turbine project, determine the retail price of electricity needed to achieve a zero NPV project, or determine the capital costs required to achieve a zero NPV project.

The impact of design choices to both the performance and costs can be considered by combining the two models.

3.2 Turbine Performance Screening Model

As was shown in Chapter 2, the performance of a turbine can be determined from the turbine's power curve and the wind speeds at the point of installation. Turbine power curves are usually described in terms of the performance characteristics listed above. We have also added a peak efficiency wind speed to allow for gradually increasing performance of the turbine at low wind speeds. The result is that the efficiency of the turbine will be assumed to follow the pattern described mathematically in equation (3-1) and shown graphically in figure 3-1. This gives an approximation of the C_p that was shown previously in figure 2-3. This efficiency represents the complete system efficiency of the turbine. While this model is a simplification of real turbine efficiencies and power curves, it captures the major features and allows the model to be used to easily value turbine performance changes.

$$C_p(v) = \begin{cases} 0 & v \leq v_{Cut-In} \\ \frac{v - v_{Cut-In}}{v_{cpmax} - v_{Cut-In}} C_{pmax} & v_{Cut-In} < v \leq v_{cpmax} \\ C_{pmax} & v_{cpmax} < v \leq v_{rated} \\ \left(\frac{v_{rated}}{v}\right)^3 C_{pmax} & v_{rated} < v \leq v_{Cut-Out} \\ 0 & v > v_{Cut-Out} \end{cases} \tag{3-1}$$

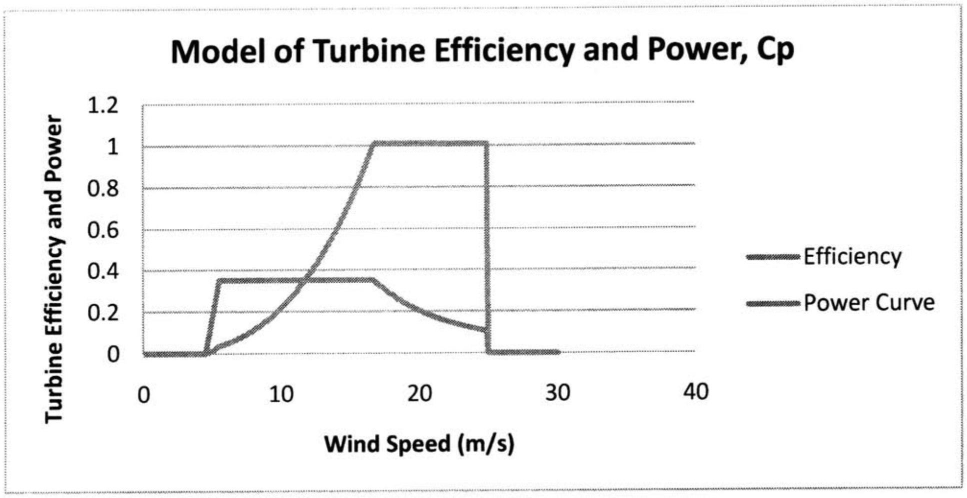


Figure 3-1: Model for turbine efficiency and power curve

For the current analysis, the v_{cpmax} will be assumed to be 1 m/s above the cut in speed.

The swept area of the turbine, A, can be implied by the rated speed and the peak efficiency of the turbine with this approach since we assume the turbine operates at peak efficiency and outputs the rated power at the rated wind speed.

$$A = \frac{2 \times P_{rated}}{C_{pmax} \times \rho \times v_{rated}^3} \tag{3-2}$$

The power curve of the turbine can be found by multiplying C_p by the Power in the wind from equation 2-1.

$$P = \frac{1}{2} C_p(v) \rho A v^3 \tag{3-3}$$

Combining the previous 2 equations gives us the power curve for the turbine:

$$P(v) = \frac{C_p(v) \times P_{rated} \times v^3}{C_{pmax} \times v_{rated}^3} \tag{3-4}$$

This equation only holds for conditions for which the rated power applies and neglects for example changes in air temperature, pressure, and density which may affect turbine performance.

The mean expected power output can be found from the power curve and the wind speed probability distribution by:

$$E[P] = \int_{-\infty}^{+\infty} f(v)P(v)dv \tag{3-5}$$

And the expected capacity factor of the turbine is:

$$CF = \frac{E[P]}{P_{rated}} \tag{3-6}$$

The capacity factor will be used as an input to the cost model.

3.3 Cost Model

The cost model will be based on determining a turbine's Net Present Value, NPV. The NPV analysis will be done using real dollars at the present time. The model will use as inputs the capital costs, yearly revenue, and expenses.

For this analysis, it is assumed that the typical customer is a home owner or small business owner who can obtain financing through a home equity loan. This will be used to determine the cost of capital. The current average rate as of April 2010 is 7.8%. (Bankrate.com 2010) The installation of a wind turbine involves several risks, but early adopters of the technology will be likely willing to assume those risks at relatively low, or possibly even no increase in expected return. However, to have a significant market to develop a specific application, a positive level of return must be available to encourage adoption. The discount rate was chosen to slightly exceed the cost of capital. For this analysis 10% is used. For simplicity, it is assumed that capital costs will be repaid over the typical turbine lifetime of 20 years.

Capital costs will be assumed to be obtained by borrowing on a home equity line of credit. The yearly payment is given by the annuity formula of:

$$A = \frac{r_c \times (1-r_t)C_0}{1-\frac{1}{(1+r_c)^T}} = c_A \times C_0, \quad c_A = \frac{r_c(1-r_t)}{1-\frac{1}{(1+r_c)^T}} \tag{3-7}$$

We will assume that capital costs are paid at time 0 and revenue and maintenance costs for a full year is realized at the end of each year. The turbine lifetime will be assumed to be 20 years.

$$NPV = \sum_{t=1}^{20} \frac{(R_t - OM_t - c_A C_0)}{(1+r_d)^t} \tag{3-8}$$

Capital costs, C_0, will include the full cost of acquiring and installing, and commissioning a turbine. The capital cost less any incentives that are available for installation, such as the US Investment Tax Credit. The revenue turbine is simply the value of the electricity generated in terms of sale price or avoided cost. For small wind installations with net metering it is the retail value of the electricity replaced by the turbine which is given by:

$$R_t = CF \times 8760 \times P_{rated} \times (E_{cost}(t)) \tag{3-9}$$

The cost of electricity will be adjusted by any available incentives on electricity production. If we want to determine the capital costs assuming that the operation and maintenance costs are a constant fraction, c_{OM}, of the capital costs:

$$NPV = \sum_{t=1}^{20} \frac{(CF \times 8760 \times P_{rated} \times E_{cost}(t) - (c_{OM} + c_A) C_0)}{(1+r_d)^t} \tag{3-10}$$

If c_A and c_{OM} are constant over the lifetime of the turbine, zero NPV occurs for C_0 such that:

$$C_0 = \frac{(CF \times 8760 \times P_{rated}) \sum_{t=1}^{20} \frac{(E_{cost}(t))}{(1+r_d)^t}}{(c_{OM} + c_A) \sum_{t=1}^{20} \frac{1}{(1+r_d)^t}} \tag{3-11}$$

If the capital costs are normalized by the turbine's rated power the capital costs become:

$$\frac{C_0}{P_{rated}} = \frac{(CF \times 8760) \sum_{t=1}^{20} \frac{(E_{cost}(t))}{(1+r_d)^t}}{(c_{OM} + c_A) \sum_{t=1}^{20} \frac{1}{(1+r_d)^t}} \tag{3-12}$$

We can find the levelized cost of energy, *LCOE*, by setting the price of energy, E_{cost}, constant over the turbine's lifetime.

$$LCOE = \frac{C_0}{P_{rated}} \frac{(c_{OM} + c_A)}{(CF \times 8760)} \tag{3-13}$$

Yearly power production is assumed constant over the lifetime of the turbine and annual operation and maintenance costs will be assumed to be 3% of the capital costs.

3.4 Summary

This model will enable the evaluation of cost and performance that is required to make small wind turbine installations economically desirable with and without government incentives. It does not consider other factors that might be considered in wind turbine performance including price premiums that customers are willing to pay for clean energy or the public relations value to commercial firms utilizing clean energy systems.

The model enables two calculations. The target cost for a turbines installed into a know wind speed and electricity rate can be determined. The levelized cost of electricity, LCOE, for a turbine installation can also be found. This allows the model to be used to determine the comparative advantage of technologies with different cost and performance features, applications with different wind speed and electricity prices, and comparison with other technologies, most notably solar photovoltaic.

Chapter 4: Selection of Applications for Small Wind Turbines Technology in Populated Areas

This chapter focuses on the various applications that have been considered for small wind turbines in populated areas. Wind turbines, even small turbines, have historically been used in rural applications or off grid applications. In this chapter the challenges and opportunities involved in selecting applications for installing wind turbines in the populated and built environments will be examined.

There are three advantages to generating electricity in urban wind installations instead of rural wind farms:

1. Can be offset or sold at the retail electricity price instead of the wholesale price
2. Avoids transmission losses
3. Does not require investment in new transmission

While wholesale electricity prices are often as low as $0.04/kWh, retail electricity prices can be as high as $0.20 cents/kWh in the US (EIA). Small urban wind installations can be designed to offset retail electricity use when installed taking advantage of net-metering or when developed using a PPA arrangement.

Transmission losses are responsible for 6.5% of the total electricity generated in the US in 2007. (EIA 2009b) These losses are part of the increased cost of retail electricity prices. Small wind installations installed where electric load is used will not be subject to transmission losses.

Urban wind installations are a form of distributed electricity generation. In distributed electricity generation, electricity is generated where it is used instead of at large centralized power plants and does not need to be connected into a transmission line with limited capacity on the electric grid or have new transmission lines built to integrate that wind power. It connects directly to user's loads and can feed back to the grid when excess electricity is being generated.

There are several challenges to building mounted and building integrated wind turbines. (Dutton et al. 2002).

1. Assessment and understanding of wind turbines
2. Effects of noise and vibration on building and occupants
3. Optimization of wind turbine designs for urban environments

4. Non-technical issues such as permitting, financing, safety, and insurance.

Additional challenges in the industry were outlined in a 2002 industry roadmap for the small wind turbine industry. They include (AWEA 2002):

1. High capital costs
2. Insufficient reliability
3. Lack of standards
4. Lack of sustained incentives

Many other aspects identified in the AWEA industry roadmap have been improved at least partially, including issues with power electronics, state incentives, interconnection standards, and undervaluation of renewable energy.

With the exception of the effect of turbine vibration on buildings, those challenges generally apply to freestanding turbines in urban areas as well. There are also four distinct market segments for small urban wind turbines. (Stankovic et al. 2009)

1. Building mounted or building integrated wind turbines
2. Small stand alone wind turbines
3. Large wind turbines sited in populated areas
4. Off grid wind turbine systems

The type of turbine is somewhat dependent on the location and application of the installation. Table 4-1 Illustrates four typical applications that will be focus of the remainder of this paper. The analysis will determine the requirements for success in each application. The wind speed ranges were estimated from the Warwick Wind Trials report which studied several building mounted urban wind turbine installations. (Encraft 2009)

Where the previous chapter provided an overview of the wind power industry in general, in this chapter the focus is on issues and challenges that must be overcome when developing urban wind installations from technological, economic, and societal aspects.

Table 4-1: Typical applications for urban wind turbine installations

Location	Application	Wind Speed (% of Wind Atlas Speed)	Reference Wind Speed for 7 m/s Wind Atlas Speed	Capacity Factor for 7 m/s Wind Atlas Speed.	Technologies Used		
					HAWT	VAWT	Multiple
Rural/ Suburban	Big Backyard	80-90%	6.0 m/s	21.1%	X		
Suburban/ Urban	Tall Rooftop	70-80%	5.0 m/s	12.9%	X	X	
Suburban/ Urban	Roof Edge	55-70%	4.0 m/s	6.3%	X		X
Suburban/ Urban	Low Rooftop	50-60%	3.5 m/s	3.9%	X	X	

4.1 Urban Wind Resources

As discussed in Chapter 2, the best wind for generating electricity is a strong undisturbed wind blowing over a smooth, flat landscape. Urban areas consist of buildings, roads, bridges, signs, towers, trees and other objects which disrupt the wind flow and increase turbulence.

The result of these obstacles to wind in the urban and suburban landscape is to raise the effective ground level for wind to the height of the surrounding structures. (Sharman 2010) Taking this view, wind turbines in the built environment need to be installed above rooftops, trees, and other significant structures in a specific area. (Heath et al. 2007) This results in two obvious locations for wind turbines. The first is to build on and above the rooftops of existing structures and the second utilizes pole mounted turbines with their own foundations away from buildings.

Figure 4-1 shows the results of a computational fluid dynamics, CFD, model of how wind flow changes as wind passes over a typical house. (Heath et al. 2007)This figure illustrates some of the technical challenges associated with harnessing the wind flow over a building through a roof mounted turbine. The wind flow appears to vary greatly and is generally not horizontal which will tend to reduce the efficiency of a wind turbine. Locations not centered on the building may see very different winds as wind direction changes. The higher above the roof the turbine is mounted, the cleaner the wind appears to be.

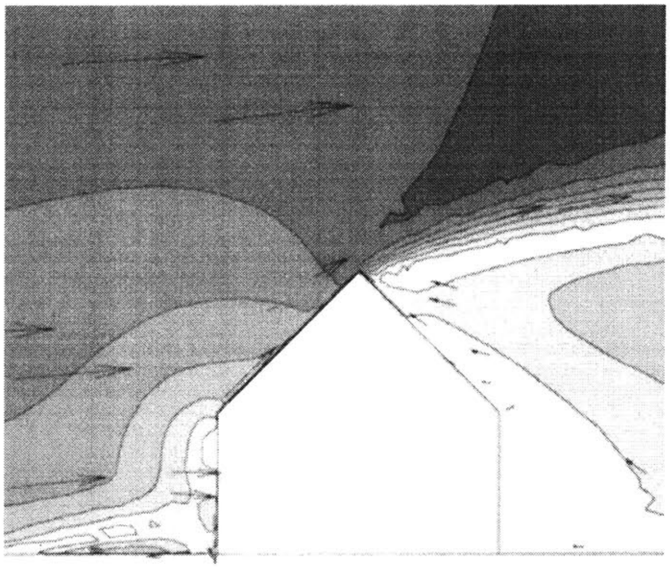


Figure 4-1: Wind flow over an isolated house (Heath et al. 2007)

Figure 4-2 is a similar model for wind flow over a typical commercial office building. Mertens has done extensive analysis of wind flow over buildings and predictes that properly sited turbines mounted on the roofs of typical buildings could double the energy output of a free standing wind turbine in the same environment. If mounted on spherical buildings the output could be 4 times as much as a free standing turbine. However, Mertens considers only the flow only a single building with the surrounding environment approximated by adjusting the surface roughness of the surrounding terrain.

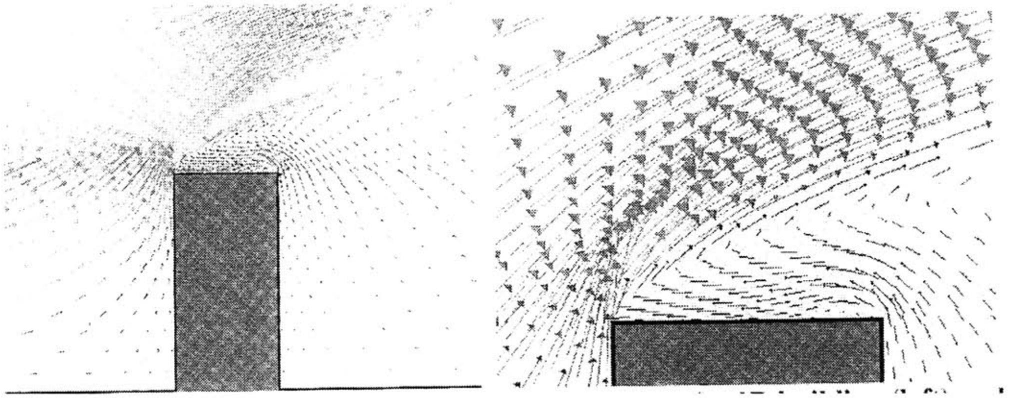


Figure 4-2: Flow over a flat roof building. (Mertens 2002)

Figure 4-3 shows the overall flow further from the house describing the area impacted by the wind obstruction created by a building. (Gipe 2009) From this diagram, which might be more typical of suburban or rural installations, it can be noted that a building disrupts the wind flow at heights up to twice the building height and up to 20 times the building height away from the building. This figure illustrates the importance of installing wind turbines above nearby obstacles and a sufficient distance away from buildings whenever possible.

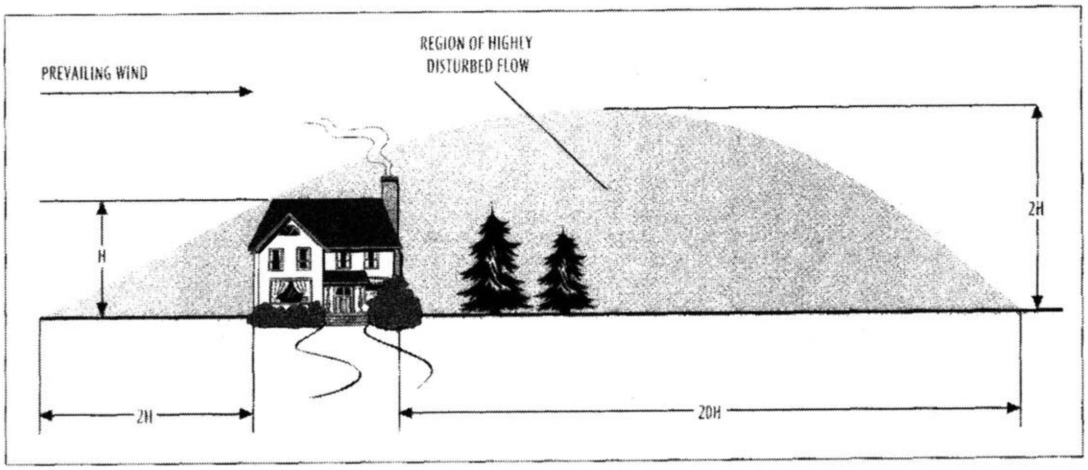


Figure 4-3: Effect of buildings on wind (Gipe 2009)

There is considerable understanding of how wind affects pedestrian comfort in cities. However, this work is only just starting to be adapted to wind turbine siting and performance. It has been suggested that urban wind tunnel effects can be used to increase the capacity factor of urban wind turbines. (Dutton et al. 2002, Heath et al. 2007) Air flow accelerates in the vicinity of buildings as the air passes by the building. It is likely that this stronger wind has increased turbulence. Figure 4-4 is a CFD model of flow around an array of buildings. It is clear there is some wind tunnel effect on the perimeter of the buildings, but the middle and trailing buildings see less of an acceleration effect. The cost of modeling and measuring an urban area to identify where urban wind tunnels are usable by wind turbines is not known. Companies such as Meteodyne are selling software to model wind flow in urban areas for wind turbine siting. (Meteodyne 2010) However, no success stories using CFD modeling were identified.

While CFD models of individual building geometries can be used to identify wind tunnel effects, when the view is expanded to involve a cluster of buildings, the applicability of the results on a single building may no longer be valid. In addition, in areas where new construction is likely, there is also a risk of a good wind location being blocked by the construction of a new building.

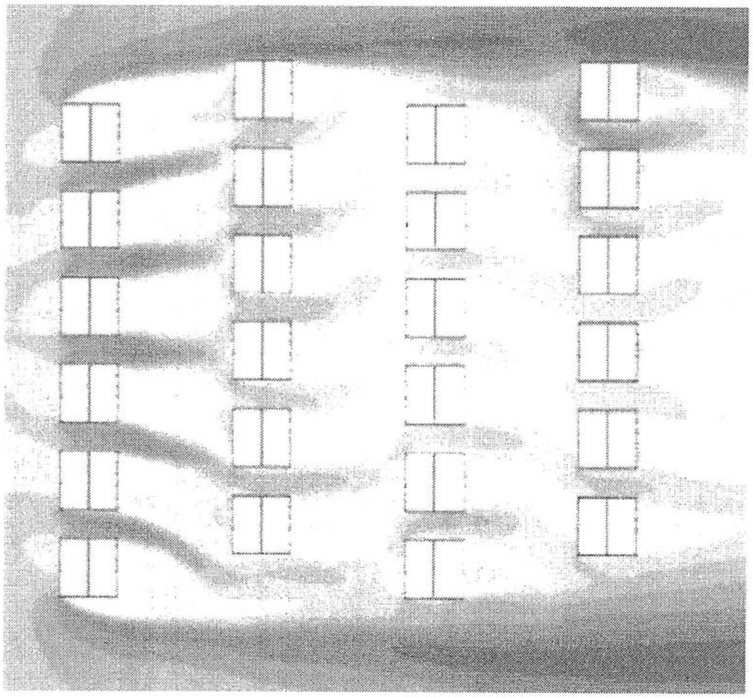


Figure 4-4: Overhead view of wind flow through an array of buildings. (Heath et al. 2007)

Adobe systems placed 20 vertical axis wind turbines each capable of 1.2 kW output on an outdoor sixth floor terrace at its headquarters in San Jose, CA. One reason noted for the location was wind tunnel effect created by the building's 3 towers that surround the terrace. Published reports indicate that the turbines experience average wind speeds of 13-14 mph or about 6 meters per second and the 20 turbines each rated at 1.2 kW are cumulatively expected to produce 50 MWh/year of energy. Although the cost of the installation is not disclosed, the turbines typically cost \$9,000 to \$12,000 installed. (Bailey 2010) Using this information, the installation cost is between \$7/Watt and \$10/Watt. Sam's Club in Palmdale, CA recently installed 17 2.4 kW wind turbines on top of parking lot light poles. This installation is expected to generate 76 MWh/year of energy.

Using this data, the predicted capacity factor for the site can be calculated. It is found by the following equation (Wizelius 2007):

$$Capacity\ Factor = \frac{Energy\ Produced\ (\frac{kWh}{year})}{Power\ Capacity\ (kW)\times 8760\ \frac{hours}{year}} \tag{4-1}$$

For the Adobe installation, the expected Capacity Factor, CF, is 24% and the Sam's club installation it is 21%. The Adobe installation is designed to specifically take advantage of wind tunnel effects of surrounding buildings. The Sam's club installation uses turbines that appear to be above the roofline to take advantage of the strong winds in the Palmdale, CA area. These values are much larger than the results of obtained in the Warwick Wind Trials or a study done for the Massachusetts Tehcnology Collaborative (Shaw 2008). Both Warwick Wind Trials and the MTC study determined an average capacity factor of 4% for the systems they studied. The Warwick study figure notes that its capacity factor is only for times when the turbines were in operation. If downtime of turbines is also considered, the warwick wind trials capacity factor was was below 1 % (Encraft 2009, Shaw 2008)

The Warwick Wind Trials performed an extensive testing of small wind turbine installations, including comparisons of actual wind conditions at turbine installation against the reference wind speeds provided by the UK's NOABL database at each turbine location. The results indicate significant adjustments downward to mapped wind speed data estimates provided by the UK's NOABL database. Only the single rural site and two of three high rise mounted turbines fell within 10% of speed estimates. (Encraft 2009)

The Energy Savings Trust also performed a series of small wind turbine trials. They conclude that location is very important for small wind turbines, and that building mounted turbines perform much less efficiently than pole mounted turbines. (Energy Saving Trust 2009)

Finally, a Cadmus study for the Massachusetts Technology Collaborative illustrates the difficulty of estimating wind speed and energy output for a typical wind installation in the urban environment. Among 19 systems installed under a program developed by the Massachusetts Technology Collaborative, in only 1 case did the system energy output reach even 50% of the installer's predicted output. And in 9 of the 19 cases, the system output less than 20% of the installer's predicted energy output. This is true even if the wind turbines were sited at least 30 ft above surrounding obstacles. Cadmus notes several reasons for the discrepancies including uncertainty in published wind resource data, surrounding obstacles, inverter efficiency, and wind turbulence effects. (Shaw 2008)

The results indicate that those turbines mounted on high rise buildings above other nearby obstructions generally saw better wind speeds than those on lower buildings and those turbines installed that were nearby significant obstructions at the turbine height.

4.2 Environmental Effects of Urban Wind

The environmental impact of rural wind farms includes determining impact on the natural environment, plant life, animal life, wetlands, the effects of noise and shadows on any nearby inhabitants, and possible impacts on aviation. For suburban and urban installations, the effects of noise and shadow are increased while the effects on an already developed landscape may be less important in many circumstances.

The impact of noise on an inhabited area may place practical limits on the design or size of turbines located in an urban area. Smaller turbines typically produce less noise. Potential impacts of flicker may limit the size and the height of the turbine, since increases both factors impact how much shadow flicker will affect nearby inhabitants.

Wind turbine vibration issues make building mounted turbines potentially unsafe. (Gipe 2009, Stancovic et al. 2009) Additionally, even when the building structure is safe, noise and vibration may prove disruptive a building's occupants. In Warwick Wind Trials of building mounted wind turbines, 7 of the 26 turbines, including all of the best performing building mounted turbines were turned off either part of the time or full time because of noise or vibration issues disturbing the building occupants. (Encraft 2009) Others have noted that rooftop mounting typically results in noise and vibration issues and that the savings from eliminating the tower and foundation of the turbine are not as significant as perceived. (Gipe 2009) However, the Boston Museum of Science has five building mounted turbines successfully installed for six months, Aerovironment turbines are successfully installed on 2 buildings in the Boston area, and Boston city hall has a roof mounted Skystream 3.7. One significant consideration might be to consider whether the building is residential, as in the Warwick Wind Trials, or commercial as in the other examples noted above.

Other environmental concerns, including those about effects on the natural environment and about wildlife, particularly birds, are of less importance in urban wind where the urban environment already has significant impact.

4.3 Urban Wind Turbine Technology

The design used for large wind turbines is primarily a three bladed Horizontal Axis Wind Turbine, or HAWT. In attempts to reduce cost and improve the performance of small turbines in much more uncertain and variable urban environments, a large number of different designs are already on the market and in development. (Sharman 2010, AWEA 2009)

A number of vertical axis wind turbines, or VAWT's, and some HAWT's that are based on similar concepts to VAWT's are on the market. Proponents of VAWT designs claim that these units are more tolerant of the turbulent and variable wind conditions that are found in urban environments and discussed above. However, there is no historical data available to confirm this claims (Stankovic et. al 2009)

Several currently available turbine designs are discussed in Table 4-2 and 4-3. Table 4-2 shows list price for turbines including the turbine's tower but before any further site preparation and installation costs. Table 4-3 shows a sample of published installed turbine costs.

A datapoint on the Proven 6 kW turbine installed by Cace has been excluded from the list in Table 4-3. The installed cost (€20,000) given was lower than the list price of the 6 KW turbine obtained from Proven's website and resulted in a cost in US dollars per watt of $4.50, significantly lower than other installations listed. Further information on how this data point was obtained was not available so it will not be considered for determining a low point for installed cost per kW.

Table 4-2: Pricing for selected small wind turbines before installation

(Windspire 2010, Southwest 2010, Proven 2010, Ampair 2010, Bergey 2010, Turby 2010)

Manufacturer	Model	Capacity (kW)	Uninstalled Price (w/Tower)	Cost ($/Watt)
Windspire Energy	Windspire	1.2	$6,500	$5.42
Turby	Turby	1.9	€13,000 ($17,550)	$9.24
Southwest Windpower	Skystream 3.7	2.4	$10,000	$4.17
Proven	7	2.8	£12,100 ($18,600)	$6.65
Ampair	6000	6.0	£18,000 ($27,700)	$4.62
Proven	11	6.0	£19,600 ($30,200)	$5.04
Bergey	Bergey-Excel	10.0	$40,000	$4.00
Proven	35	12.8	£45,900 ($70,600)	$5.52

Table 4-3: Currently available small turbines with example installed costs (Cace et al. 2007, Bailey 2010)

Manufacturer	Model	Rating	Cut In Speed	Rated Speed	Installed Cost (€1 = $1.35)	Cost per Watt
Southwest Windpower	Skystream 3.7	2.4 kW	3.5 m/s	11 m/s	$14,000	$5.83
Windspire Energy	Windspire	1.2 kW	3.5 m/s	13 m/s	$10,500	$8.75
Fortis	Montana	2.7 kW	2.5 m/s	10 m/s	€16,495 ($22,300)	$8.25
Turby	Turby	1.9 kW	3.5 m/s	12 m/s	€17,838 ($24,100)	$12.67
Energy Ball	V100	0.5 kW	2.0 m/s	15 m/s	€5,700 ($7,700)	$15.39

While the more established firms such as Southwest Windpower, Bergey, and Proven have all used the familiar 3 bladed HAWT turbine design, many of the new entrants in the field are developing VAWT or other style turbines including Windspire Energy (formerly Mariah Power) and Turby. As more data becomes available on VAWT designs the value of both their performance compared to that of HAWT designs, and their potentially more acceptable aesthetic design may become a key factor for shaping the future of wind in both urban and non-urban areas.

As stated earlier, capital pricing is a significant issue. While installation at every site must be considered when determining installation costs, costs for small wind turbines before installation range from a minimum of $4/Watt and up for the turbine, and installed costs ranging from $5.83/Watt and up. This compares to the $3.50/Watt low end price stated by AWEA in their 2008 Small Wind Turbine Tarket Report (AWEA 2009) cited in Chapter 2.

4.4 The Urban Wind Market and the Small Wind Industry

Several mid-size and large wind turbines have been installed in urban areas. In the Boston, Massachusetts area there are several large turbines that are listed in Table 4-4. Selected smaller turbines installed around the Boston area are shown in table 4-5. There have been numerous installations in the last 3 years, particularly in small turbines.

Table 4-4: Large urban turbines (>=100 kW) in or near Boston, MA (AWEA 2010)

Location	Turbine	Year Installed
Hull, MA	Vestas – 660 kW	2001
Dorchester, MA	Fuhrlander – 100 kW	2005
Hull, MA	Vestas – 1.8 MW	2006
Chelsea, MA	Turbowinds - 600 kW	2008
Medford, MA	Northern Power – 100 kW	2009
Newburyport, MA	Elecon - 600 kW	2009
Winthrop, MA	(2) Solaya - 600 kW	2009

Table 4-5: Selected smaller turbines installed around the Boston area.

Location	Turbine	Year Installed
Beverly, MA – Solar Now	Bergey – 10 kW	1997
Boston, MA – City Hall	Skystream 3.7 – 2.4 kW	2008
Cambridge, MA – Harvard University	(6) Aerovironment – 1 kW	2008
East Boston, MA – Logan Airport	(20) Aerovironment – 1kW	2008
Allston, MA – Harvard University	(2) Bergey Excel – 10 kW	2009
Boston – Museum of Science	Proven – 6 kW	2009
Boston – Museum of Science	Skystream 3.7 – 2.4 kW	2009
Boston – Museum of Science	Mariah Windspire – 1.2 kW	2009
Boston – Museum of Science	(5) Aervironment – 1kW	2009
Boston – Museum of Science	Swift – 1.5 kW	2009
Cambridge – MIT	Skystream 3.7 – 2.4kW	2010*

*Planned Installation

The first study of the wind turbine market was produced by A.D. Little for NREL in 1981. Over 20 years later, the American Wind Energy Association, the main US wind industry association, produced a 20 year roadmap for the small wind turbine industry in 2002, with updated market reports released in 2005, 2007, 2008, and 2009. (AWEA 2002, 2005, 2007, 2008, 2009) This pattern indicates the increased interest in small wind power over recent years.

In the US, there are 80 MW of installed small turbine capacity, compared to 35 GW of total wind capacity and 350 MW of total solar photovoltaic capacity. (AWEA 2009) For the small wind industry to have a significant impact it needs to grow substantially in the near future and AWEA predicts the market will grow to 1500 MW of capacity by the end of 2013.

The number of turbine manufacturers has grown significantly in the last few years. In 2006, there were roughly 25 manufacturers producing turbines with an estimated 42 additional companies planning to enter the market. (AWEA 2007) At the end of 2008 there were 36 companies in production and another 180 companies planning to enter the market (AWEA 2009). This is a 40 % increase in the number of companies producing turbines and a 450 % increase in companies planning to enter the market.

Small wind turbines can be installed in urban, suburban, or rural areas. Installations in rural areas are likely to involve different challenges than those in more populated areas and may include wind turbines installed to power structures that are "off-grid". In rural areas, tall installations far from buildings and trees are preferred as this is where the best wind resources will be found. In urban environments, effects such as aesthetics, noise, and shadow flicker are often more significant. Identifying locations with a good wind resource is also challenging since buildings, trees, and other features of urban and suburban landscapes disrupt the wind flow. AWEA has traditionally calculated market size based on properties with more than ½ or 1 acre depending on the size of the turbine. (AWEA 2005, AWEA 2009)

While urban wind turbines are unlikely to achieve the economies of scale of rural wind farms, there are opportunities for cost effective development of wind resources. At first glance these include net metering, where electricity can be sold or offset retail electricity use, and little or no investment in transmission is required. The disadvantages include permitting costs, public safety.

While large wind turbines are mostly of a standard 3 blade horizontal axis design, smaller wind turbines have been designed with diverse approaches. In addition to a number of models that look like scaled down versions of large turbines, several vertical axis turbines and unique horizontal axis turbines are being sold or designed for the market. Many are designed to be building mounted. Vertical axis turbines have been advertised to work better with turbulent wind conditions found in urban areas. There are no published reports directly demonstrating this effect.

Small wind turbines have normally been sold through distribution channels and purchased by home owners or businesses who can offset on site electricity use with the installation of a wind turbine. However, in the solar market, installations done according to power purchase agreements are common, where the developer owns the equipment and sells electricity to the home or business at retail electricity rates. The developer retains rights to incentives which is used to supplement the income made through the sale of electricity. DeerPath energy is one company using this business model in the small wind market. Growth in the use of PPA's is predicted in the wind market under the current incentive structure.

Figure 4-5 shows the growth of the small wind turbine market in recent years and AWEA's projected growth for the next 4 years. They predict an over 10 fold increase over 2009 sales by 2013. AWEA predicts over 500 MW of small wind installations per year in 2012 and 2013 and almost 2 GW of installed small wind capacity by the end of 2013.

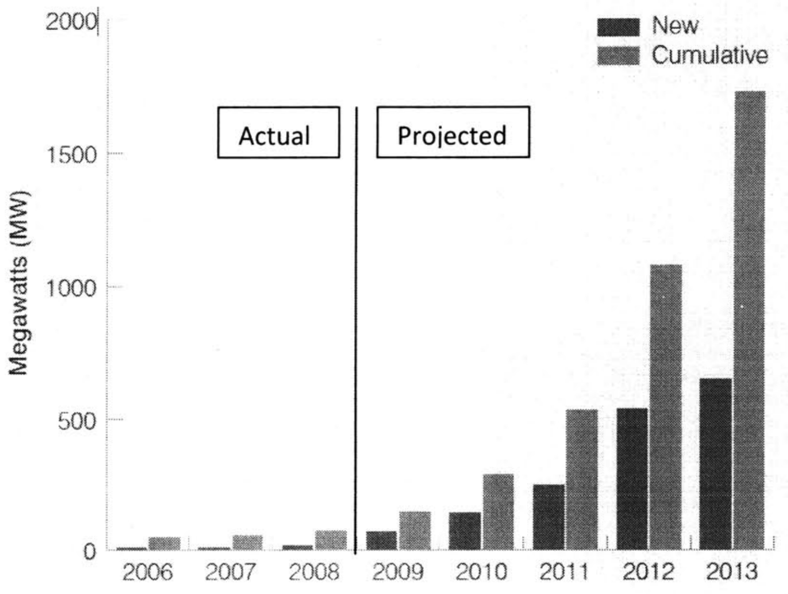


Figure 4-5: Actual installations and installed capacity through 2008 and projected installations through 2013 (AWEA 2009)

4.5 Policy and Incentives

As wind projects, particularly urban projects, are rarely competitive with conventional power generation, governments have provided various incentives to encourage development of wind power projects. In the US, the Database of State Incentives for Renewable Energy and Efficiency (DSIRE 2010) is a good source for researching the incentives available in a specific state.

At the federal level in the US, the current incentive is a production tax credit, which currently provides 2.1 cents/kWh for power produced in the first 10 years of operation but this is only available to commercial operations. In addition, there is also a 30% investment tax credit against capital costs for wind turbine development for wind turbines under 100 kW. There are both a corporate and residential version of the investment tax credit. (IRS 2009)

A variety of incentives are available at state levels. The most common being renewable energy credits that can be obtained where states have Renewable Energy Standards or Renewable Portfolio standards. Several states have enacted these standards which require a certain percentage of the state's electricity to be provided from renewable sources such as wind and solar. Utilities are responsible for meeting the standard and will pay independent producers of renewable electricity for the right to use that generation to meet their renewable energy requirement. The amount paid is usually driven by an open market where verified credits may be sold by generators and purchased by utilities that need to meet the standard.

Net metering is available in some form in most of the United States. Net metering is useful when the owner of a turbine may not be able to use all of the electricity generated by a wind turbine at the time it is generated. For example, if a turbine is operating at its maximum output and electricity use is low because no one is home, the excess electricity must be sold to the grid operator. Net metering mandates that the utility must pay retail price to purchase this electricity. Thus, the owner of the turbine pays only for the net electricity purchased from the grid over the long term. Different jurisdictions have different policies on exactly how this arrangement is implemented.

Many states offer incentives similar in nature to the federal investment tax credit. Massachusetts offers a capacity credit based on the size of the turbine installed and the amount of energy produced in the first year of operation for wind turbines up to 99 kW of nameplate capacity. This incentive can be up to $4/watt, and can cover a significant portion of the installation costs of a small wind turbine. (Renewable Energy Trust 2010)

4.6 Evaluation of Applications

The model developed in Chapter 3 is applied to the applications for small wind turbines applications described in this chapter. Figure 4-6 shows the relationship of wind speed and retail electricity price to find the customer's willingness to pay for the capital cost of a turbine. On top of this, we can denote the typical wind speeds that are available for various applications and the cost points for turbines.

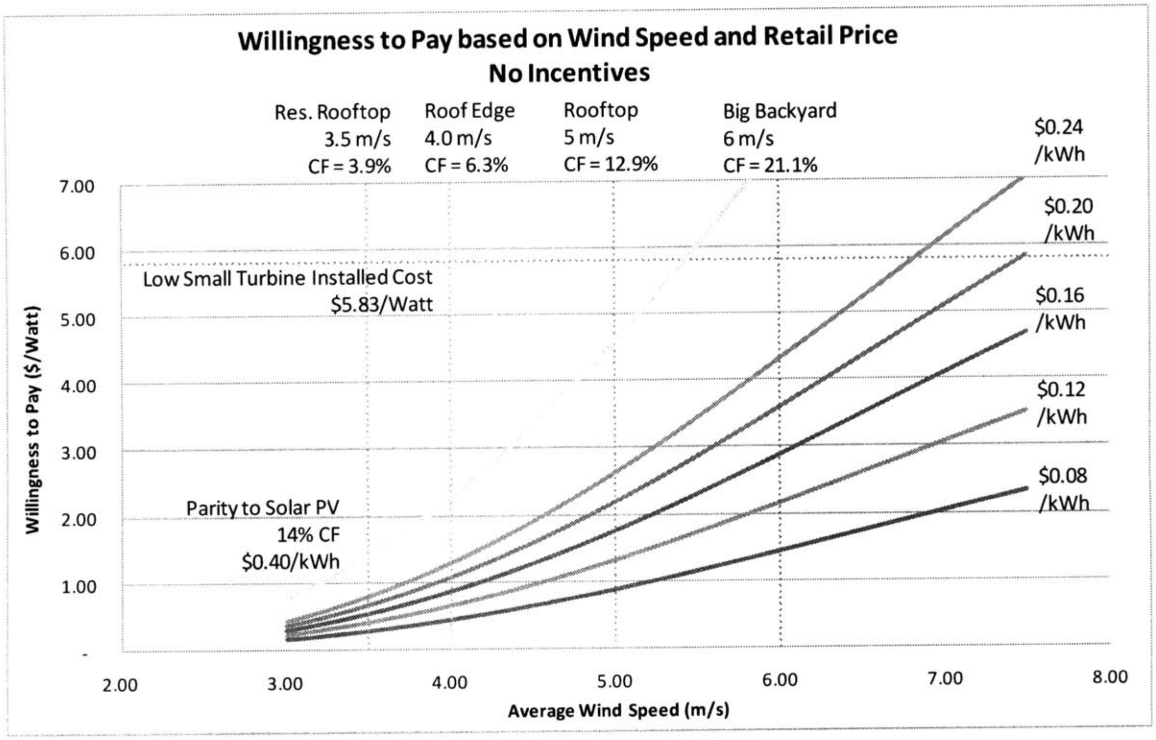


Figure 4-6: Willingness to pay based on wind speed and retail price without incentives

As a result of the cubic relationship between wind speed and power content of the wind, small increases in the wind speed result in significant allowable increases in capital cost. We have also shown a target curve for price that makes a wind system economically equal to solar PV. This curve assumes a Solar PV cost of $5/Watt and a capacity factor of 14%, typical for Boston, Massachusetts using NREL's PVWatts application (PVWatts 2010). The target price for wind at each wind speed is found by:

$$C_w = C_S \frac{CF_S}{CF_w} \tag{4-2}$$

Where C_w is the target capital cost of wind, C_s is the capital cost of solar, and CF_w and CF_w are the wind and solar capacity factors. This simple equation assumes that the differences in operation and maintenance costs between wind and solar systems are not significant and that the value of electricity provided by the two systems is equivalent. However, higher wind operation and maintenance costs and the daytime availability of solar photovoltaic systems will mean that target costs for small wind systems to be competitive with PV will likely need to be somewhat lower than illustrated in Figure 4-6.

It is seen that the current low expected installation price of $5.83, wind will be more cost effective than PV for an average wind speed at or above 5.5 m/s.

In Figure 4-7, federal incentives are included in calculating the customer's willingness to pay. The current federal incentive in the US for residential wind energy systems is a 30% tax credit on the turbine and installation costs (DSIRE 2010). The result of the federal incentives is to make a $3.5/Watt system able to be installed at locations where the average wind speeds which are over 1 m/s slower than otherwise economical.

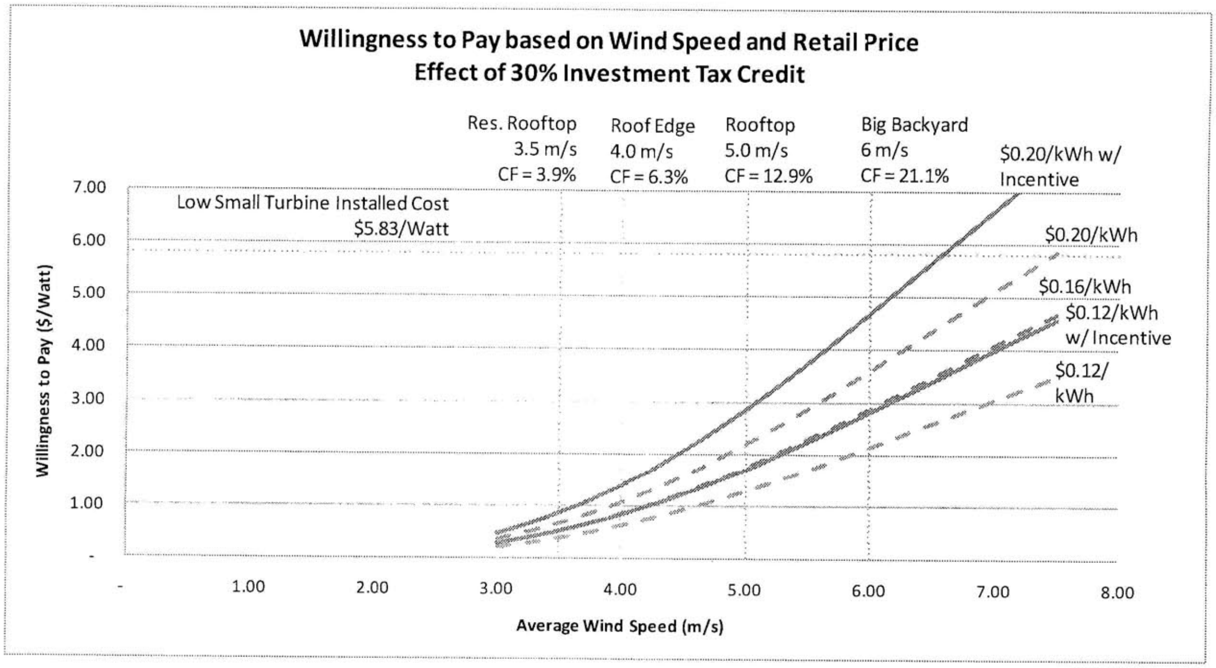


Figure 4-7: Willingness to pay based on wind speed and retail price with incentives

Table 4-5 shows the resulting willingness to pay with and without the federal incentives for the applications identified in Chapter 3.

Table 4-6: Willingness to pay for applications (Typical wind speeds at $0.16/kWh electricity price)

Application	Wind Speed (m/s)	Unicentivized Target Cost ($/Watt at $0.16/kWh)	Target Cost with Incentives ($/Watt at $0.16/kWh)	Value of Incentive ($/Watt)
Back Yard/Unobstructed Rooftop	6 m/s	$3.09	$4.41	$1.32
Obstructed Rooftop	5 m/s	$1.86	$2.66	$0.80
Roof Edge	4 m/s	$0.95	$1.35	$0.40
Residential Rooftop	3.5 m/s	$0.62	$0.88	$0.16

The results of this evaluation indicate that identifying locations with the most available wind is extremely important in determining the economic success of a small wind turbine project. This is a result of the cube relationship between wind speed and energy content of the wind discussed in Chapter 2. The increase in target capital cost from locations with 5 m/s average wind speed to 6 m/s average wind speed is over 60%, in line with increase of 20% in wind speed and potential 73% increase in wind energy content.

The 30% tax incentive improves the economics of the installations, but further cost reductions are needed to drive market growth based on economic considerations by customers given our target wind speeds for various applications. Only niche markets with high wind speed and high electricity price or additional incentives approach economic attractiveness with current pricing and incentives. The 30% tax incentive appears comparable to a $0.04/kWh production incentive.

4.7 Evaluation of Savings for Wind Combined with Emergency Power

To consider the application of wind turbine working with or in place of an emergency power generator, the power generated by the wind turbine is used to replace high value power produced by a generator and depending on the system design, capital costs may also be reduced by considering the avoided costs of using a smaller generator in place of larger one or not using a generator at all. Further, if a battery is added to the wind system, it may have ancillary use in demand response or other applications when the risk of power failure is low.

The baseline case evaluation of the wind turbine in this application will be a generator system without wind. This will include the capital cost of installing and operating the generator for an expected number of hours every year. The cost/year of owning and operating a generator system with a 20 year lifetime would be the capital cost amortized over the lifetime of the system plus the yearly operating costs. Only fuel costs for generating emergency power are considered for operating costs.

$$\frac{Cost/Watt}{Year} = \frac{C_0}{\sum_{t=1}^{20}\frac{1}{(1+r)^t}} + CF \times T_{Run} \times E_{cost} \tag{4-3}$$

The second case will be a wind turbine in addition to a generator system. In this case, the operating costs for the generator will be reduced by the amount of power provided by the wind during an outage. This equation assumes that the output of the wind turbine will not exceed the demand of the system.

$$\frac{Cost/Watt}{Year} = \frac{C_0}{\sum_{t=1}^{20}\frac{1}{(1+r)^t}} + \left(CF_{gen} - \frac{P_{wind}}{P_{gen}} CF_{wind}\right) \times T_{Run} \times E_{cost} \tag{4-4}$$

Table 4-7 shows the effective Cost/Watt of using a wind turbine. The savings gained by considering the use of a wind turbine in this application is less than 1 cent/watt even at the highest wind speeds.

Table 4-7: Reduction in effective capital cost for wind turbine providing emergency power

Average Wind Speed (m/s)	Cost/Watt/Year Savings
4.5	$0.0012
5.5	$0.0021
6.5	$0.0032
7.5	$0.0043

The savings gained using a wind turbine with emergency power generation are very small, and do not result in meaningful cost advantages over regular wind turbine installations that do not work with emergency backup power systems.

4.8 Challenges and Strategies for Application Selection

An overview of wind turbine applications commonly cited for small wind turbine installations was given, and typical wind resources for those applications were estimated from various sources in the literature.

Applying the model developed for determining the target costs reveals that only the best installation applications result in economically viable projects even with current government tax credits for 30% of the installation cost.

The built environment, including urban and suburban landscape, has a significant impact on the overall wind speed. Choosing applications with high wind speed is critical, and the built environment can make this a significant challenge because of both effects on wind speed and local regulations that limit the size, height, and location of turbines. Wind speed is important even with the availability of government incentives and the presence of high retail electricity prices.

Use of wind turbines as a supplement to emergency power generation systems does not result in significant cost savings at reasonable expectations for use of the emergency backup power system.

Chapter 5: Strategy for Technology Improvements in Small Wind Turbine Technology

There are over 200 companies competing in the small wind turbine market (AWEA 2009), and the previous chapter highlighted the need to improve the cost and performance of wind turbines in order to grow the small wind turbine market. Several possible improvements to wind turbine technology have been put forth including capturing wind energy at lower wind speeds, turbines promising improved efficiency. This chapter uses the model developed in Chapter 3 to value different approaches to technology development so that they can be put in perspective with other business strategies.

The two most common improvements pursued in technology are low wind speed operation and higher efficiency. Efficiency gains can be found in several areas of the system, most notably in the rotor blades, the generator, and the inverter and electronics. Efficiency gains can also be found by obtaining better turbine response to changes in wind speed direction and wind speed.

5.1 Evaluation of Low Wind Speed Turbines

One of the main marketing points from many new entrants into the small turbine market is that a turbine is capable of generating wind at a low wind speed. There are two possible mechanisms for generating power at low wind speeds. First, is total system efficiency improvement at low wind speeds. The second is an increase in turbine swept area to increase the available power at low wind speeds. This method will also result in a lower rated wind speed. Table 5-1 lists a number of available small wind turbines that operate operate with cut-in speeds below 3 m/s. Note that these products have non-standard ratings. The WindTronics turbine has a swept area of about 1.4 m^2, consistent with a 600 watt turbine.

Table 5-1: Available small wind turbines advertising low cut-in speeds

Manufacturer and Model	Cut-In Speed	Design	Cost	Notes
WindTronics GT6500 (WindTronics 2010)	2 m/s	10 Bladed HAWT	\$6,500	Rated 2.2 kW at 17 m/s. Peak output 4 KW at 35 m/s.
Energy Ball V100 (Home Energy 2010)	2 m/s	Novel HAWT	\$4,600 (McDermott 2008)	Rated 100 W @ 10 m/s. Peak output at 17 m/s.

The results of turbine performance versus cost are shown in Figure 4-4 as the turbine cut in speed is varied to as low as 2 m/s and as high as 4 m/s. There are modest gains in performance that allow a roughly 10 % increase in component cost. However, the turbines are still far from economically viable at low wind speeds even if this performance improvement is obtained at no cost compared to existing turbines.

The analysis of turbines with a large rotor diameter is more complicated. In this case, the cost structure of the system changes significantly. If the rotor of a turbine is increased, the foundation and tower costs will increase with the area of the rotor in order to capture the increased loads on the turbine during periods of the maximum design wind speed. The rated speed of the turbine will also decrease significantly as the larger rotor area captures more power at lower wind speeds and the rated power is reached at a lower wind speed.

The potential improvement can be judged by evaluating how much of an area increase is necessary for the wind speed at the desired cut-in speed to contain the same energy as the "usual" cut-in speed of 3.5 m/s. The revised turbine swept area, A1, is simply the original area, A0, multiplied by the cube of the wind speeds:

$$\frac{A_1}{A_0} = \left(\frac{v_{0Cut-In}}{v_{1Cut-In}}\right)^3 \tag{5-1}$$

The new rated speed would be given by:

$$\frac{v_{1Rated}}{v_{0Rated}} = \left(\frac{A_0}{A_1}\right)^{1/3} \tag{5-2}$$

Table 5-2 shows the corresponding turbine area and rated speeds for new cut in speeds obtained with larger rotors.

Therefore, on a target cost per unit power scale, these turbine designs look like they can be significantly more competitive than turbines with other designs. Figure 5-1 shows the production increase for turbines as a result of cut in speed. The increase in production from changes in cut-in speed is low. In Figure 5-2, the target costs are shown for turbines in terms of cost per watt, and significant improvement is seen. Most of this improvement comes from the reduction of the turbine's rated speed, causing the turbine to operate at its maximum power over a larger portion of the wind speed distribution curve. To account for the increased rotor size, cost per swept area of the turbine is shown in

Figure 5-3 for two average wind speeds. This illustrates that the actual improvement of the turbine cost has not improved significantly, though for turbines installed at lower average wind speeds the optimum cut in speed and rotor size may change. The improved performance at low wind speed will be relatively small compared to the large decrease in performance from the reduced wind speeds.

Table 5-2: Normalized swept area and turbine rated speed for cut-in speed changes

Cut-In Speed	A_1/A_0	D_1/D_0	V_{1rated}
2.0	5.36	2.32	7.43
2.5	2.74	1.66	9.29
3.0	1.59	1.26	11.14
3.5	**1.00**	**1.00**	**13.00**
4.0	0.67	0.82	14.86
4.5	0.47	0.69	16.71

5.2 Evaluation of Efficiency Performance Improvements

A number of manufacturers claim significant efficiency improvements over the standard 3 blade HAWT design. Improved efficiency results in a reduced rotor area to achieve the same performance. There are two ways to evaluate improved turbine efficiency. First is to allow the rated speed to be reduced to reflect that the rated power will now be obtained at a lower wind speed. The second is to reduce the swept area of the blades and analyze the turbine cost in terms of cost per swept area. Table 5-3 shows the turbine parameters for both scenarios.

Table 5-3: Turbine rated speed and swept area for efficiency changes

Efficiency (Baseline case 35%)	Rated Speed at Original Area (m/s)	Normalized Swept Area at Rated Speed of 13 m/s	Normalized Diameter at Rated Speed of 13 m/s
30	13.7	1.17	1.08
35	**13.0**	**1.00**	**1.00**
40	12.4	0.88	0.94
45	12.0	0.78	0.88

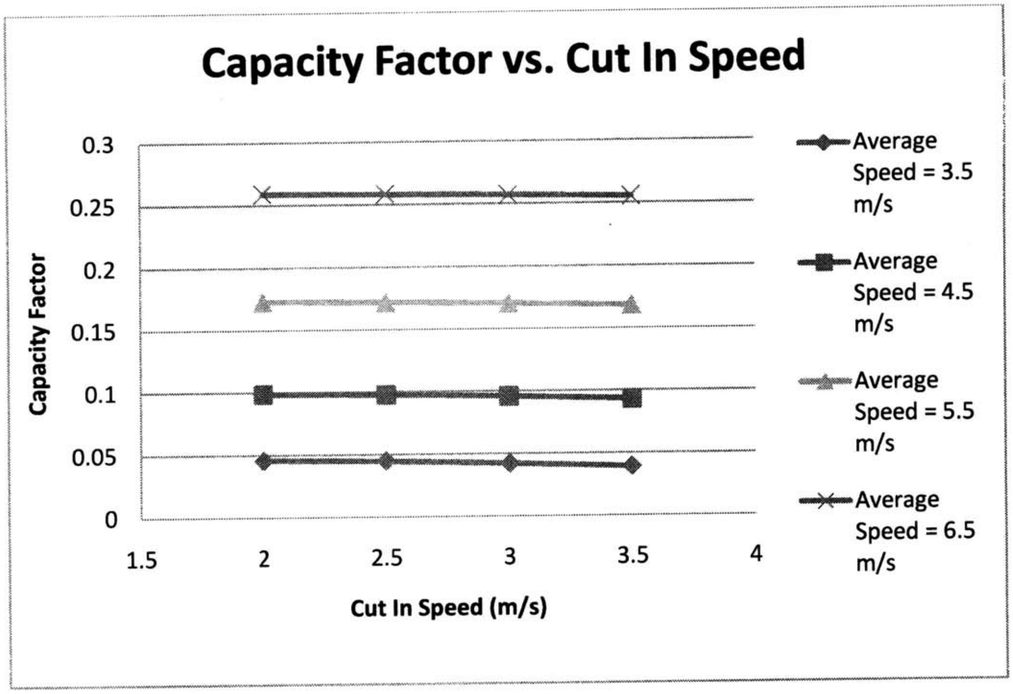


Figure 5-1: Effect of changing cut-in speed on turbine performance

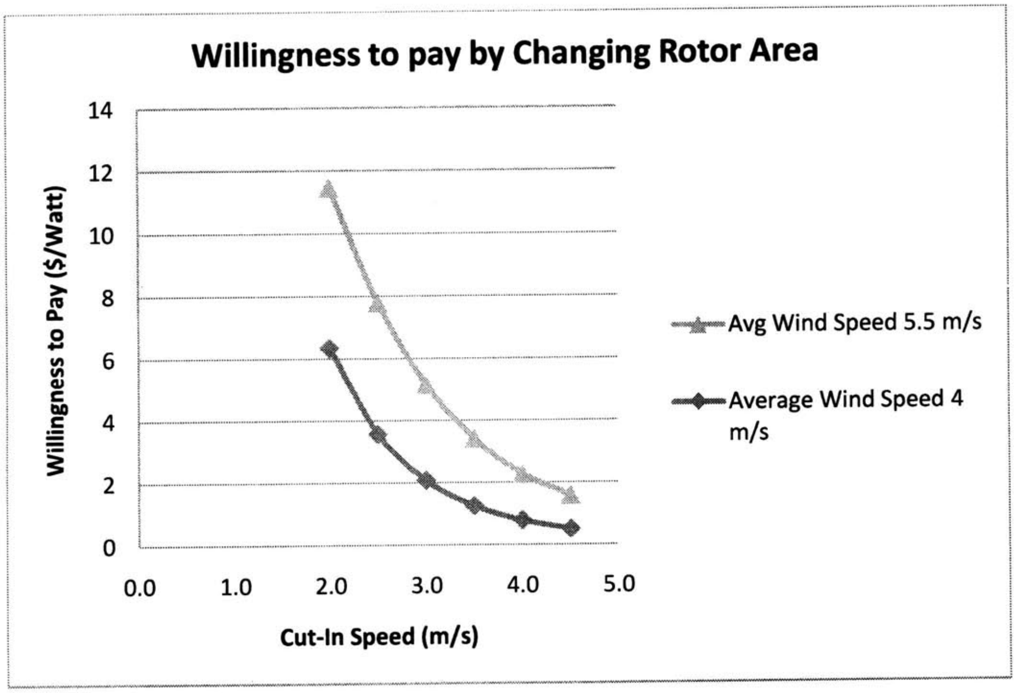


Figure 5-2: Effect of changing rotor size to achieve lower cut-in and rated speed

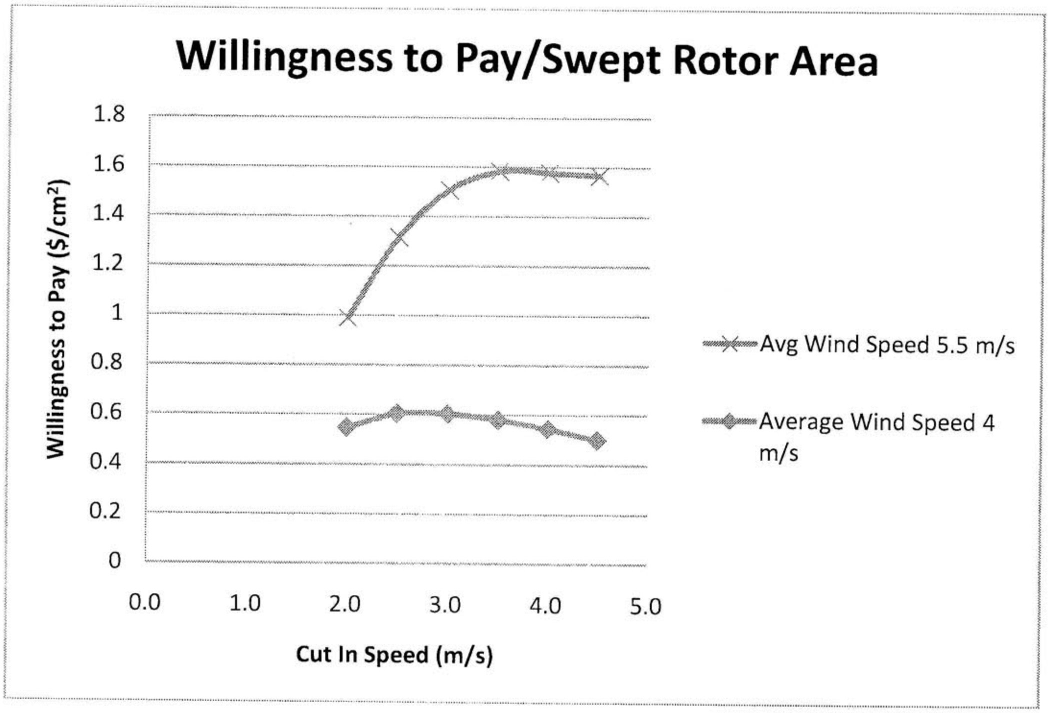


Figure 5-3: Effect of changing rotor size on willingness to pay per swept area

Figure 5-4 shows the results for the turbine efficiency. Both analyses yield similar results and show the benefits to improvements in turbine efficiency. The slope of both lines for the 5.5 m/s case is approximately 0.09/Watt/% Efficiency. However, at the lower average wind speed of 4 m/s the additional allowable capital cost is only 0.035/Watt/% Efficiency. Efficiency gains at lower wind speeds are significantly less valuable than if a turbine is installed in an area of higher wind speed. This reinforces the need to install turbines at locations with good wind speeds. Efficiency gains have little impact for poorly sited wind turbines.

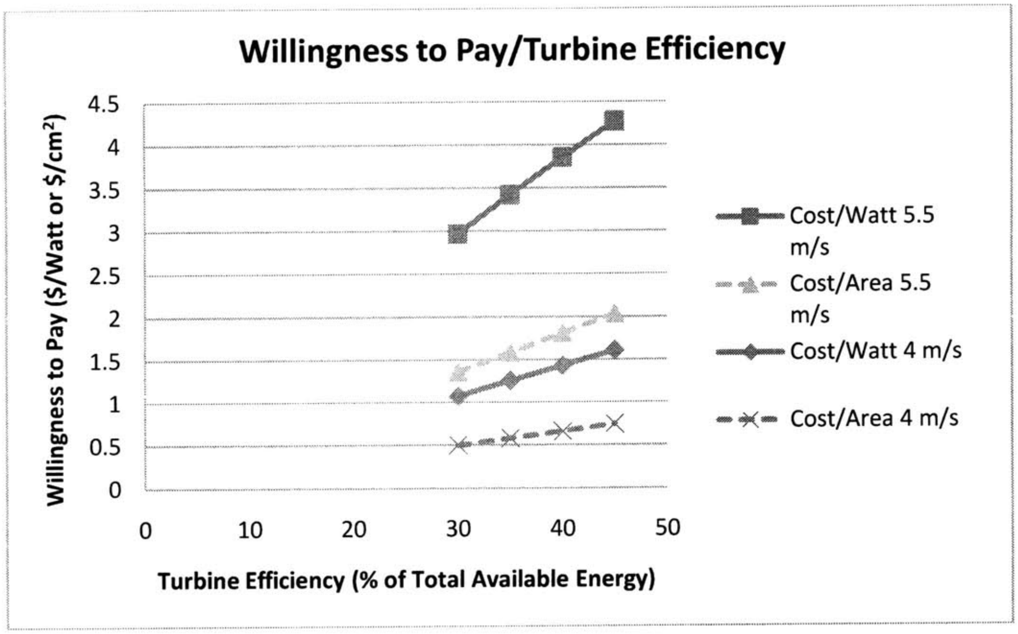


Figure 5-4: Willingness to pay for efficiency changes

5.3 Challenges and Strategies for Technology Improvement

In the previous chapter, the main challenges to developing successful turbine projects are in locating good wind resource in areas with high economic incentives and high electricity price. This chapter identified somewhat smaller opportunities do exist in improving turbine efficiency. Improvement is also possible if the rated speed can be lowered without significant impact on turbine cost resulting from the increased turbine area. Improvements in capturing energy at low wind speeds are less valuable, as lower speed installations do not result in economically feasible installations. The remainder of this paper will examine how these results can be applied with business strategy frameworks to develop recommendations to firms in the small wind market.

The results also reinforce the need to have a good wind speed condition. Efficiency gains for poorly sited wind turbines do not have a large impact on target cost when compared to turbines sited in better wind conditions. Better efficiency will not compensate for poor siting. Companies should focus on improved siting over improved efficiency.

Chapter 6: Challenges and Business Strategies for Accelerating Diffusion and Adoption of Small Wind Turbines

Building on the evaluation of target costs in Chapter 4 the evaluation of business strategies used in the design, manufacture, and installation of small wind turbines is examined.

6.1 Cost Structure of Wind Turbines and Impact on Turbine Manufacturing

The previous chapter illustrated the cost benefits of several potential improvements in small wind turbine technology. In Chapter 4, it was noted that costs for turbines have stopped declining in recent years. Current list pricing, as of April 2010, for selected small wind turbines is shown in table 4-2.

The data in table 4-2, gathered from company websites, is exclusive of installation costs, including assessment and permitting costs. One specific notice is that the data in the table does not illustrate any specific economies of scale related to the turbine cost.

The cost of a small wind turbine comes from five areas listed in Table 6-1, and the data there indicate that foundation and installation costs are likely to consist of 20% to 25% of the total installed cost of the turbine. While the small size and privately held nature of companies in the small wind industry make it difficult to detailed assessment the cost structure of small wind turbines, Table 6-1 compares the cost breakdown a 1.5 MW wind turbine compared to general HAWT and VAWT cost breakdowns.

Table 6-1: Cost breakdown for large wind turbines, HAWT's, and VAWT's

Item	Large 1.5 MW Turbine Cost ($/Watt) (George and Schweitzer 2008)	HAWT (Viterna and Ancona 2009)	VAWT (Viterna and Ancona 2009)
Rotor, Blades, and Hub	19%	27%	34%
Drive Train and Nacelle	31%	23%	17%
Tower and Foundation	11%	22%	17%
Generator and Electrical	13%	13%	17%
Transport and Installation	26%	15%	15%

Small turbine manufacturers have predicted that scale up can reduce the cost of small turbines to under $2/Watt. (AWEA 2005) The basis of this prediction is unclear, though it can be reasoned that this cost is exclusive of tower and installation costs which themselves are estimated to be 37% of a HAWT turbine's installed cost. Even with these reductions in turbine cost, installed cost using the above data will still be around $4/Watt. The source of cost reductions in all aspects of a wind turbine installation can be found through:

1. Scale up of the manufacturing process can reduce turbine cost.
2. Streamlining of the assessment and permitting process.
3. Reduction in the balance of station costs, including installation.
4. Improved turbine design and more cost effective materials.
5. Reduction in component costs.
6. Turbine performance improvements.

Many small wind turbine projects are likely to have a relatively fixed cost for installation rather than costs that scale with turbine size as most of the analysis assumes. In particular, certain project costs—such as site selection and permitting, are not likely to depend on the size of the turbine installed. In many cases, discontinuities may be found when size limits for permitting, net metering, or incentives are reached. In table 6-2 the development tradeoffs between going to slightly larger turbines in populated areas are presented.

Table 6-2: Issues and tradeoffs between turbine sizes

Cost	Large Turbines will likely see improved LCOE or cost/Watt. Small turbines will be affordable for customers to pay full purchase and installation cost up front. Smaller turbines will be perceived as lower risk investments by customers.
Site Electricity Use	Larger turbines may generate more electricity than can be used behind the electric meter over a long time period. Under some net-metering plans, this may result in a lower cost for excess energy generated.
Permitting	Individual small turbines make less noise, have smaller shadow impact, and have less visual impact. They are likely to face less local opposition. Local regulations will limit the maximum size of turbines in certain applications and utilities will limit the size for net-metering.
Maintenance	Since O&M is labor intensive and labor time may not scale with turbine size, larger turbines will likely see lower O&M costs as a function of the capital cost and lifetime cost of the turbine.

While current turbine pricing does not conclusively indicate that there economies of scale in using larger turbines, certain aspects of turbine installation including permitting, interconnection, labor, and equipment are likely to be relatively for smaller turbines, so some economies of scale can be assumed.

6.2 Evaluation of Small Wind Turbines on the Technology and Market S curves

Technology development and diffusion of technology into the market are frequently described using what are known as S curve frameworks. The S curve is characterized by initially slow rates of technology development and market development. The rates of diffusion and adoption gradually increase until the technology approaches performance limits or market becomes saturated. After this point, improvements in technology or increased market adoption slow until the technology becomes obsolete. Figure 6-1 is a general overview of the technology and market S curve frameworks.

Small wind turbine technology, and wind turbine technology in general, has seen relatively little improvement in the last decade even as the market for the technologies has grown significantly. If data for the change in turbine cost/performance over time, and capacity factor over time are examined, we see relatively little improvement in these important metrics. Figures 6-2 shows the cost/MW for large wind turbines, and figure 6-3 shows trends for small wind systems over the last several years. Figure 6-4 shows the capacity factors for large wind turbine projects has changed over recent years has changed very little. Note that costs in terms of dollars/Watt have increased slightly in recent years. Some of the cost increases are tied to commodity prices for materials such as steel and copper. (AWEA 2008) Meanwhile, another key performance metric, capacity factor, appears to have also flattened for large projects. There is no evidence of significant technological advances in small turbines in recent years. However, manufacturers do predict that some manufacturing cost savings and technological improvements are still possible, so there is still some room for improvement on the technology S curve for small wind turbines.

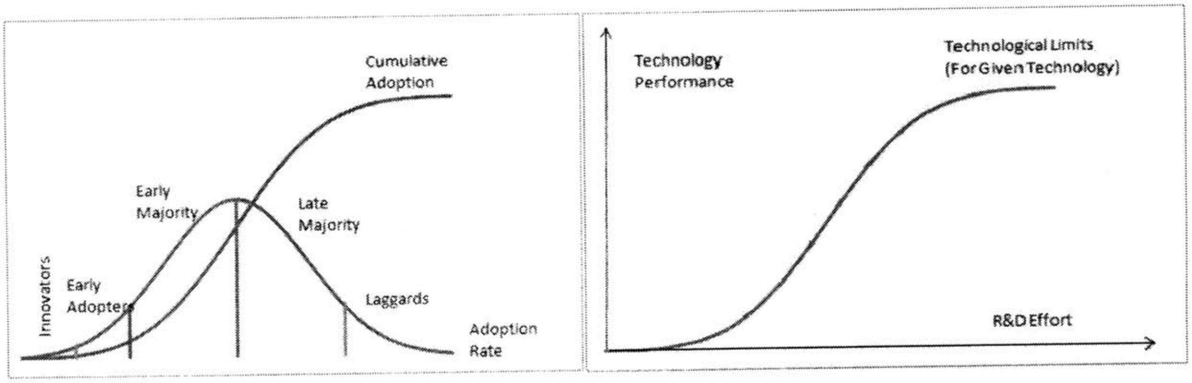


Figure 6-1: S-Curve Frameworks for Market Adoption and Technological Progress

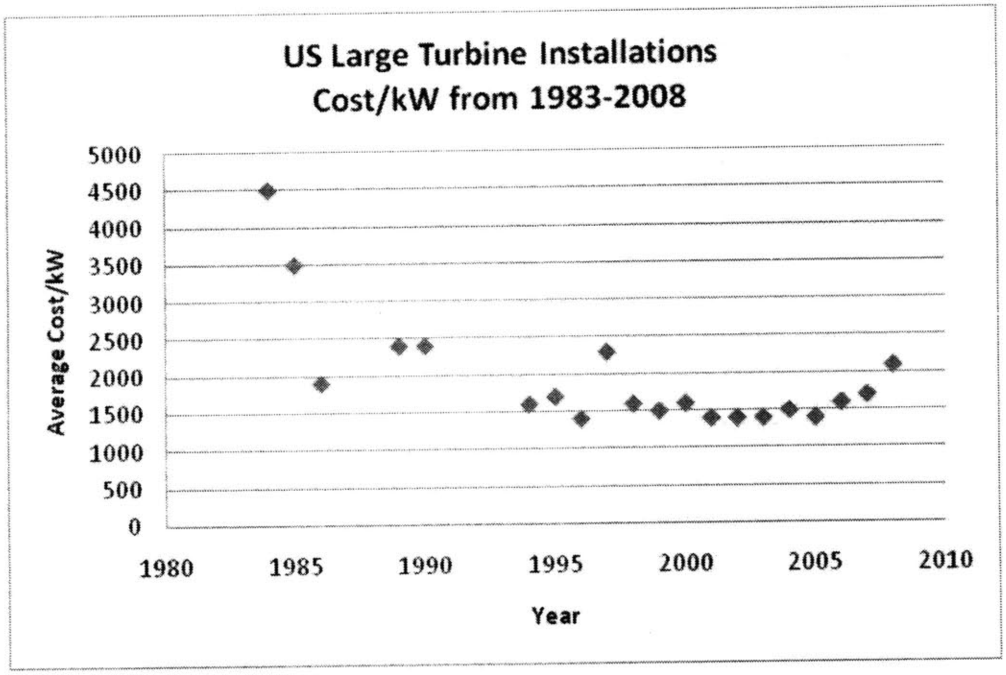


Figure 6-2: Trends for installed cost/capacity of large wind turbine projects. (Wiser and Bolinger 2008)

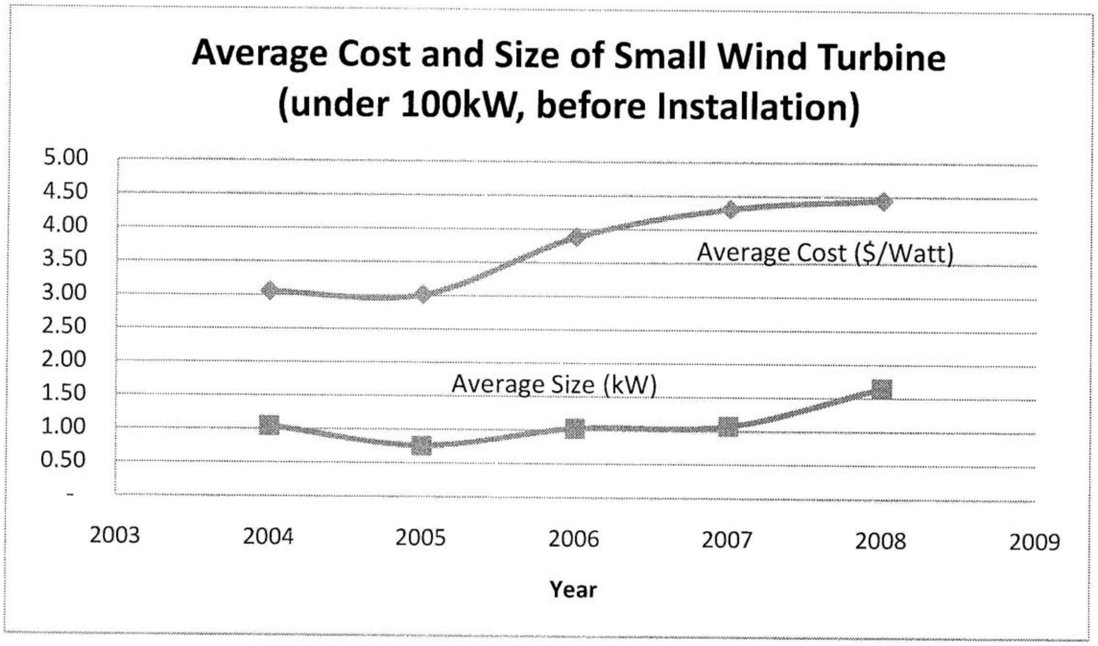


Figure 6-3: Average Cost per Capacity for Small Wind Turbine Installations in the US. (AWEA 2008, 2009)

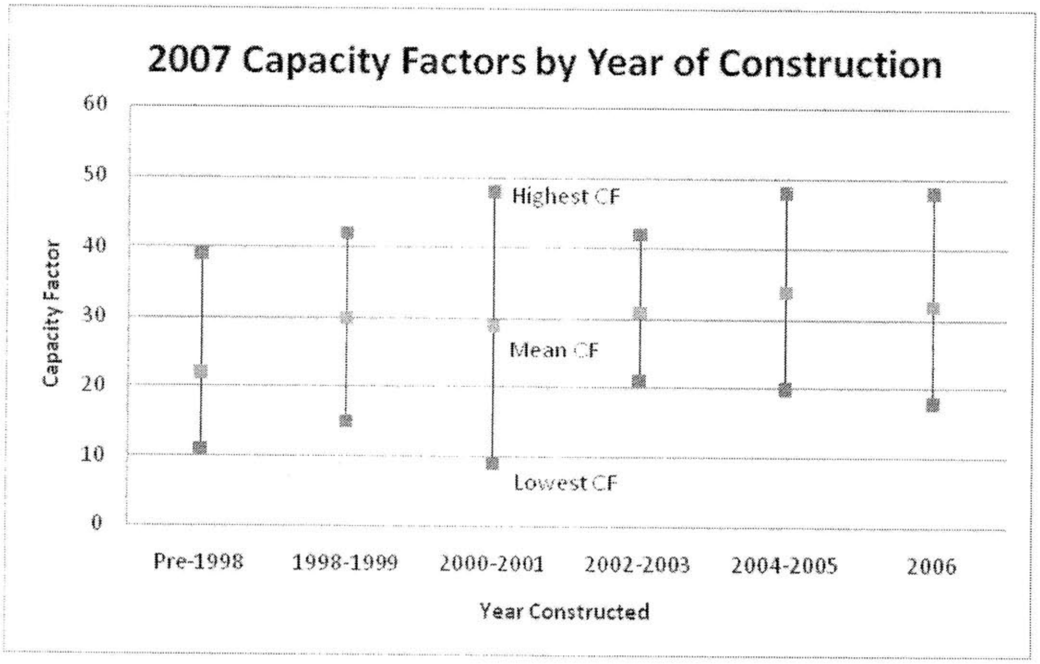


Figure 6-4: Capacity factor improvement for large turbines from 1998 to 2006 (Wiser and Bolinger 2008)

A few manufacturers of small wind turbines have been in the market for 20 or more years. (Sharman 2010) The maturity of these companies, along with the lack of measureable improvement in turbine costs, suggests that the technology currently used in small wind turbines is mature, and will not see much additional improvement without a significant additional innovation in turbine technology.

The market S-curve indicates a different picture about the development of the market. The market diffusion model divides the market into innovators, early adopters, early majority, late majority, and laggards. (Rogers 1995) Figure 6-5 shows that in 2007 and 2008, significant growth began in the small wind turbine market. Figure 6-6 also points to the shift in the small wind market from off-grid systems to grid tied systems, a trend which is critical to seeing significant growth in the small wind market.

In the United Kingdom, renewableUK, formerly BWEA, the British Wind Energy Association, reports similar trends for the UK market, indicating that the growth in small wind extends beyond just the US market. (renewableUK 2009)

This data and the forecasts put forth by both AWEA and renewableUK suggest that the small wind turbine market is entering the early adopter portion of the market S-curve. Early adopters are typically customers who have high value application and are willing to tolerate some level of behavioral change or inconvenience to use the new technology. (Moore 1991) Figure 6-7 shows how we position small wind turbines on the technology and market S-curves.

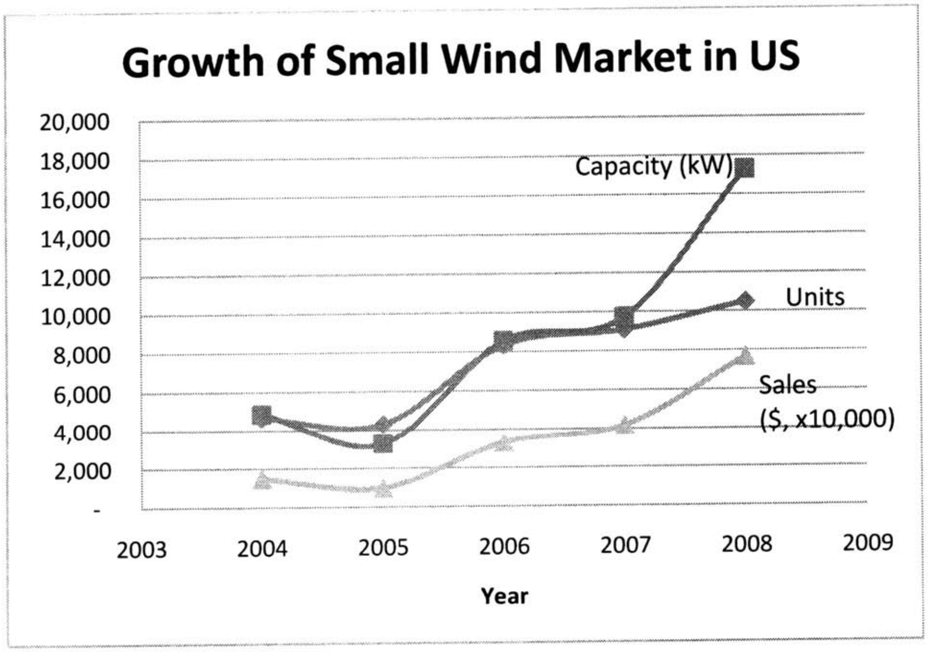


Figure 6-5: US Market Growth in Small Wind Turbines (AWEA 2008, 2009)

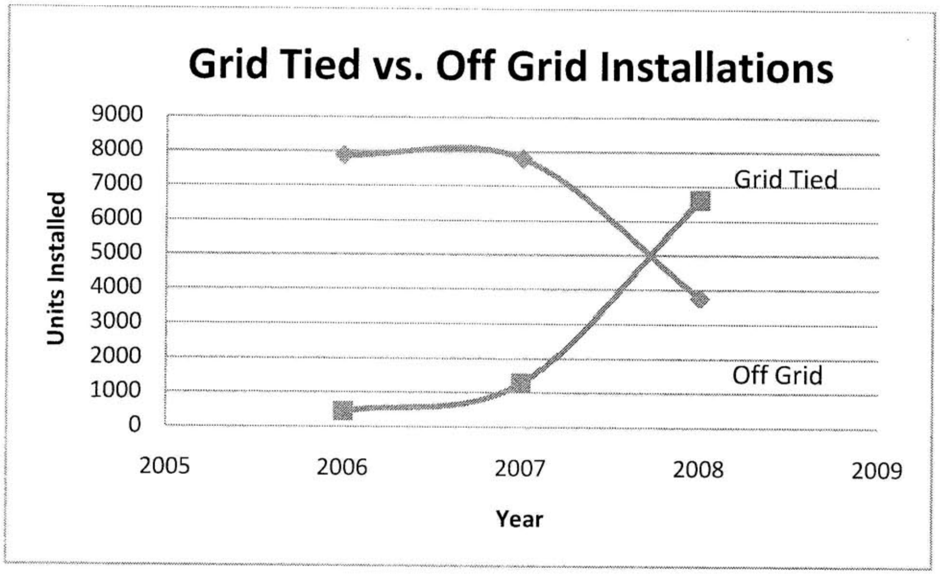


Figure 6-6: Transition from Off-Grid to Grid Tied Systems in US (AWEA 2008, 2009)

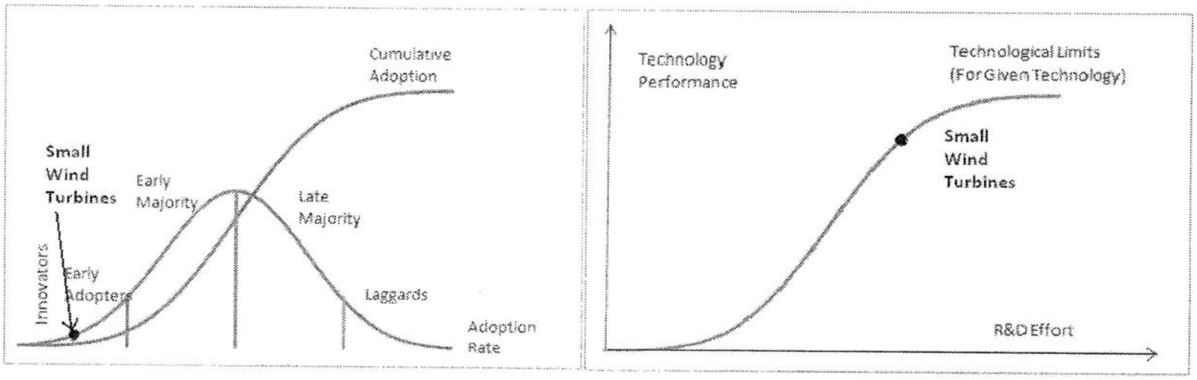


Figure 6-7: Assesment of Small Wind Industry on the Market and Technology S-Curves

An important decision for firms is to predict how small wind turbine technology will go through the diffusion and adoption process along the market S-curve, and then position themselves to take advantage of the diffusion and adoption process. Two models for technology diffusion are considered, Probit and Epidemic. (Geroski 2000) The first is Probit adoption, where individual users do a cost benefit analysis, and adoption rate is governed by the users individual preferences. As the technology matures, the cost benefit analysis becomes favorable for larger portions of the market. The second is Epidemic adoption, where adoption increases as information becomes more widely available.

While adoption of small wind seems primarily a Probit adoption scenario, where improvements in the performance of the product drive adoption, attention to techniques to further epidemic adoption should not be ignored. Most people generally think of solar photovoltaics when they think of renewable energy. Attention to promoting epidemic diffusion can help bring more attention to the small wind industry as a legitimate alternative to solar.

One simple observation when considering Probit adoption along the market S-curve is that the effective discount rate is going to increase as the market moves along the market S-curve. While the early adopters may be willing to incur economic and other costs to generate their own electricity from wind, later adopters will require increasing amounts of financial return, lower switching costs, and lower behavioral costs in order adopt wind as a distributed generation technology. As the market for wind turbines grows, factors such as reliability and limiting capital investment will become increasingly important. In Chapter 4, the benefits to limiting operation and maintenance costs were appearant. Beyond the cost component for maintenance, many potential customers will be resistant to technology that requires regular or is likely to require unscheduled maintenance, particularly when electricity from the grid has no similar requirement.

As wind turbines, particularly those in a populated area, are usually very noticeable in populated areas. Because of how easily they are noticed, in addition to the increasing level of awareness to environmental issues surrounding energy use, they are likely to serve as conversation starters. In particular, because early adopters will share certain demographic and psychographic characteristics, the early adopters are likely to have conversations with those later in the early adopter category and those in the early majority of the adoption curve. While the occasional wind turbine will likely spark curiosity, the experiences of the early adopters will be important in convincing the next group of adopters that wind turbine technology is valuable.

For both the incumbent and entering businesses in small wind, it is valuable to understand how the market dynamics will affect each firm's strategy. Figure 6-8 presents a framework for assessing first mover advantage based on the pace of technology growth and the pace of market growth. (Suarez and Lanzolla 2005) As established previously, the pace of technological evolution in small wind turbines is relatively slow, while market growth, incentivized by government policy, is occurring quickly. This puts small wind turbines firmly in the "market leads" category. Long term advantage is likely in this scenario, assuming that the incumbent firms have the capacity to scale up to match market growth. To sustain market advantage, incumbent firms require the capital and resources to scale as the market grows.

		Pace of Market Evolution	
		Slow	Fast
Pace of Technology Evolution	Slow	Calm Waters	Market Leads
	Fast	Technology Leads	Rough Waters

Figure 6-8: Framework for first mover market advantage (Suarez and Lanzolla 2005)

In addition to assessment of established firms ability to maintain their market position, it is useful to understand how new technology innovations will best be introduced into commercial production. With over 200 firms operating in the small wind space, established firms must be able to differentiate between firms with technology innovations with commercial potential and those whose technology will be not be successful in the marketplace.

One useful framework assesses the ability of start-up firms to protect their intellectual property from innovation against the ability of incumbent firms to build on their existing assets. This framework is shown in Figure 6-9. (Gans and Stern 2003) For a majority of turbine technology innovations, the existing assets of the incumbent firms will continue to add to the value proposition of wind turbines. These assets include supplier networks, distributor networks, and tacit market regulatory and market knowledge in addition to their manufacturing capabilities.

		Incumbent's Assest Contribute to Value Proposition	
		No	Yes
Start-Up can protect innovation from incumbent	No	Attacker's Advantage	Reputation-Based Ideas Trading
	Yes	Greenfield Competition	Ideas Factories

Figure 6-9: Commercialization strategy (Gans and Stern 2003)

However, it is not clear ahead of time if innovations will be easily protected by start-up firms. In either case, startup firms require the complementary assets of established firms to reach the market, the degree to which they can protect their technology innovation will determine how successful these firms are at capturing value. If their innovations can be protected, then start-ups will likely willing partner with existing firms for development. If their innovations cannot be protected, then start-up firms face a challenge of how to best capitalize on their innovations. Since technology progress is perceived to be rather slow, established firms do not need to pay significant premiums for such technology improvements, particularly when they can be developed internally.

6.3 Challenges and Strategies for Turbine Implementation

AWEA identified several key market barriers in their 2007 Small Wind Turbine Global Market Survey. (AWEA 2007) The top market barriers included:

1. Cost to consumer
2. Restrictive zoning
3. Lack of financial incentives
4. Lack of sustained incentives and incentives matching those for competing sources
5. Visual Impact/Community Opposition
6. Low Public Awareness

Additional barriers worth considering as the market grows include:

1. Reliability
2. Competition from other energy sources beyond incentives.

Three of the challenges are directly related to the turbine cost, and the other two incentives are related to permitting and approval for installation. The report also notes that consumers desire a payback period of less than five years, while small wind turbines typically range from 6 to 30 years.

The relatively small size of the wind turbine market made extensive investment in improved turbine or manufacturing technology difficult. The recent growth in the market has led to several wind turbine manufacturers raising venture capital in order to expand operations. Table 6-3 lists several recent investments into the wind turbine market.

Table 6-3: Recent Venture Capital Funding in Small Wind Turbines
(Ampair 2010, Southwest 2010, VentureWire 2010, Sharman 2010)

Firm	Date	Investment
Ampair	April 2010	$3 Million
Windspire Energy	April 2010	$3 Million
Southwest Windpower	April 2009	$10 Million

With the rapid near term growth in the wind power industry, firms will invest in improving turbine technology, scaling up of manufacturing operations, and expanding their product lines.

As the market grows, a key question facing firms in the market is how to best capture the forecast growth in the small wind turbine markets. Looking at the work on market S-curves, the near term growth lies primarily with early adopters. Early adopters are likely to have several of the following characteristics:

1. Off grid
2. High electricity price
3. Good local wind resource
4. Availability of Government incentives
5. Ease of siting (i.e. large property, few obstructions)
6. Environmentally conscious

As the market for small wind turbines grows, they will need to see significant cost improvement in order to expand the market beyond the early adopter phase. In addition, the installation process will need to become increasingly standardized, and later adopters will be less willing to participate in long assessment, permitting, and installation processes.

6.4 Strategies for Acceleration Adoption of Small Wind

Applying the frameworks and considering the Challenges outlined above, several strategic decisions of firms in the market will be critical to not only accelerating the adoption of small wind, but capturing value in the small wind market going forward. One of the most important elements of strategy for firms will be to capture as much of the growing market as possible. To do this, the models for technology adoption are used including considering the characteristics of early adopters, and the probit and epidemic diffusion models.

Three of the early adopter characteristics: electricity price, wind resource, and incentives, apply to broad geographic regions. In the US, prices and incentives are likely to be similar across entire states while wind resource will be similar across somewhat smaller regions in some states. All three of those characteristics contribute significantly to the economic success of a small wind turbine project. The off grid market will likely remain a niche market and if current trends continue will be an increasingly smaller portion of the small wind industry. Off grid turbines also tend to be smaller, and a trend toward larger turbines is anticipated, segmenting the off grid and grid-tied markets by turbine capacity.

Other early adopter characteristics, including the environmental awareness, ease of siting, and high electricity use will vary over any geographic region. The ease of siting a turbine will potentially vary from urban, to suburban, to rural areas, but may be locally more consistent as effects such as building height, lot size, and presence of tall trees may depend on a specific urban, suburban, or rural neighborhoods.

Such areas are likely to have higher concentrations of early adopters willing to invest early in small wind technology. Another challenge to increasing adoption is determining the best size of turbine for a specific project. This size may vary significantly from site to site, and having an optimally sized turbine for a project will help all parties capture the most value.

In order to capture a larger portion of a target market along the market S curve, the risk to the customer must be reduced or the return to the customer must be increased. A Government incentive using a feed-in tariff, where wind turbine electricity is guaranteed a minimum price, are an effective tool in providing incentives and removing potential downside risk for turbine installations.

Another option is a power purchase agreement, or PPA. Under a PPA, the turbine is installed at the customer site by a third party who retains ownership of the turbine but charges the customer for the electricity it produces. In this way, the customer pays the bill just like an electric bill. This is useful for larger potential wind turbine customers who may not be able to or willing to invest the capital cost of turbine but are still willing to invest in wind power through a long term purchase agreement. This can be particularly effective for larger systems where capital costs are high.

While there has not yet been price reduction in the small wind market, recent growth in the market and the raising of capital by firms such as Southwest Windpower, Ampair, and Windspire Energy suggests that manufacturing economies of scale may result in price reductions in the near future. In addition, the relative pace of market growth compared to technology growth suggests that investment in manufacturing and sales capacity is required in order to achieve and maintain market leadership.

In addition to targeting the proper markets, firms also need to consider their product development, technology development, and manufacturing strategies.

Price reductions from economies of scale will result in increased potential economically attractive projects and are more attainable than those from technology investment. Additionally, investment in manufacturing competency will help capture more long term value. Investment in efficiently deploying projects in the field will result in the establishment of a supply chain infrastructure that will also continue to generate value in the long term. In contrast, technology advancements at the high end of the technology S curve are often small and difficult to protect through IP and use as competitive advantage.

One way to achieve reduction in the costs of assessment, permitting, and installation is to generate a large number of projects in limited geographic area so that certain costs shared across projects can be reduced through resource sharing. For example, if several projects are undertaken simultaneously in the same area, there is potential for cost sharing of equipment for foundation construction and turbine installation. Labor costs may also be reduced as installers working more frequently on wind turbine projects become more efficient with their installation.

Manufacturers should also consider how to develop their product portfolios. The average installed turbine size is increasing and their is potential to capture economies of scale as turbines increase in size, though cost increases. In press releases for their recent investment, both Southwest Windpower and Ampair suggest that expansion of the product line will occur in the near future. Concerns about size, weight, loading and cost make it difficult to maintain a high percentage of common components across different turbine sizes. However, owners of wind turbine systems will have very different capital cost thresholds for purchasing small wind systems. Thus, small wind systems designed for customers who are absolute price sensitive and larger systems for customers able to capitalize on the economies of scale could be a viable approach to maximizing market position.

Given manufacturers are likely to have limited resources to develop an extensive product line, limiting their product line of two main turbine designs is advised. One is a small turbine, with low absolute capital cost, that can be purchased and installed outright by a large enough portion of the market. The second is a larger turbine that offers better returns to scale and can serve large commercial customers, be efficient enough to lend itself to financing and PPA arrangements. Larger turbines can also be marketed to community wind cooperatives.

If we review the first mover advantage presented earlier, it can be seen that while progress on technology is slow, progress in the market is accelerating. This leads to a situation where the market leads adoption and those companies quick to grab market share will be able to use that to their long term advantage. Therefore, companies such as Southwest, Ampair, and Windspire Energy who are actively raising capital and putting themselves in a position to capitalize on market growth will have an advantage over firms unable or unwilling to raise capital to expand, or on firms focusing on developing new technology instead of products and manufacturing capability.

New technology firms entering the market would also be advised to bring products to market at soon as possible to take advantage of the potential for first mover advantage or consider partnerships that enable them to take advantage of other company's manufacturing capabilities. Once market growth accelerates, it will become difficult for firms to enter the market and for firms which have fallen behind to catch the market leaders without significant advantage over the market leading firms. This advantage does not need be technical, but could be an architectural innovation in the way turbines are developed or brought to market. This type of innovation would not be a better turbine technology, but a better turbine archticture or business model. These innovations are particulary difficult for incumbent firms to spot and respond to in the market. (Christensen 1992)

In light of the slow pace of technology assets and the anticipated strength of incumbent firms, start-up companies need to ensure that they obtain the strongest possible protection for their intellectual property. It will be difficult for start-ups to enter the market directly once growth accelerates, so they will need to partner with existing firms to commercialize their technology. If they cannot obtain adequate patent or other protection, they will have little bargaining power when creating a commercialization agreement with established firms.

6.5 Allowing for Turbine Upgrade

A final strategy is to consider is the upgrade of installed turbines with successful operating histories that indicate the wind resource at the turbine is ideal for a larger wind turbine. In many cases the wind resource will be relatively uncertain since no formal wind measurement is done to predict the wind resource. Once the turbine is installed, its operating history is generally recorded by the turbine or an external data logging system.

This data can be used to a perform a post installation wind assessment with the intent to increase the capacity of more successful installations where enough wind resource makes the upgrade cost effective.

One option for turbine upgrades would be to design flexibility for expansion into the turbine system using engineering real options analysis to determine the costs and benfits of this approach. (deNeufville 2010) However, it is assumed that most small wind turbine installations are designed either to meet a target level of electricity use or fit within a fixed budget. Therefore, there is little additional benefit to be derived from this approach because the flexible expansion will either not be needed as electricity needs are met, or will not be affordable because the owner does not have sufficient funding.

However, there appear to be few technical challenges to removing an installed turbine and erecting a larger turbine in its place. Such a replacement would likely require replacing the entire turbine installation, including the foundation. The removed turbine and tower would still be viable product and could either be sold used or refurbished.

If the owner of the turbine does not have the resources to upgrade but is agreeable, alternative financing arrangements such as PPA's could be used to implement the upgrade so that the homeowner has incentive to allow the upgrade. This gives the homeowner the option to get the same benefit from windpower with no additional risk or capital investment.

Figure 6-10 illustrates how the strategy could be implemented. Challenges associated with this approach include:

1. Number of installations which meet criteria will be small.
2. Negotiations with the turbine owner to permit upgrade.
3. Permitting the site for a larger turbine.
4. Incentives must be available for the turbine upgrade and they will likely be near the new turbine incentives.
5. Removal costs of the turbine must be recouped.
6. The removed turbine must have significant residual value.
7. Site preparation for the larger turbine must be accomplished with little added cost.
8. Used turbines may be seen as threatening new turbine sales, limiting manufacturer support.

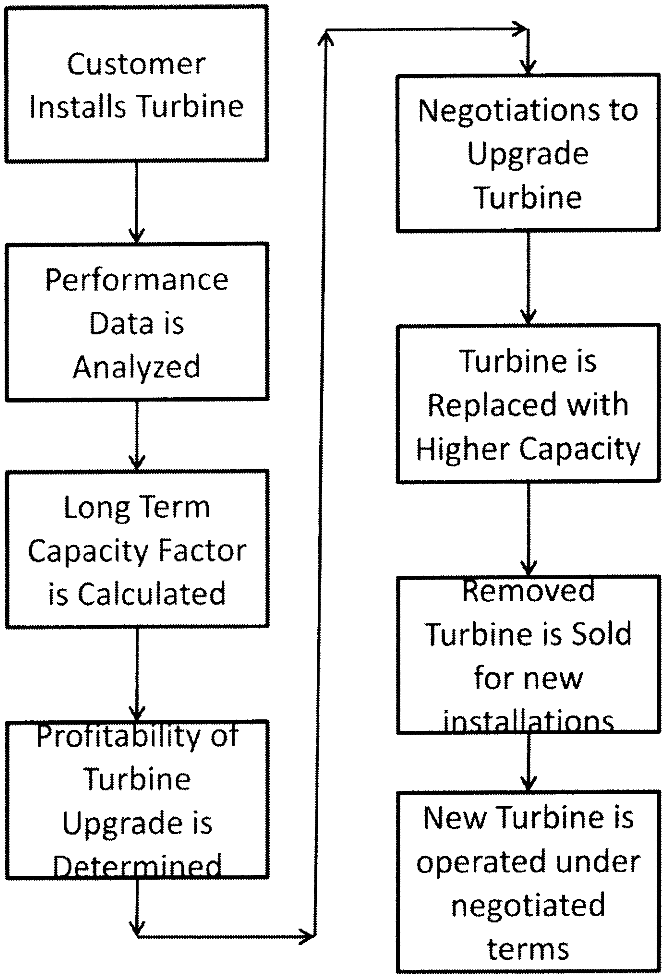


Figure 6-10: Approach to upgrading turbines with demonstrated capacity factors

However, where possible, this solution provides a low risk opportunity to deploy larger wind turbines in proven installation locations. Successful implementation of the program might require changes to existing regulations, and will make used turbines available to the market at lower prices, allowing more price sensitive buyers to purchase turbines. And while manufacturers of the smaller turbines will not wish to support disassembly and reinstallation of used turbines, for manufacturers such as Proven, where the larger turbine will be from the same manufacturer, more support may be possible.

In order for this approach to be economically viable, an individual project would need to meet the following cost guidelines where the additional revenue generated by the turbine exceeds the upgrade and transactions costs.

$$PV = (SV_{Old} - C_{New} + C_I - C_T) + \sum_{t=1}^{T_{old}} \frac{E_{Cost}(t)\times 8760\times CF\times (P_{New}-P_{Old})}{(1+r)^t} + \sum_{t=T_{old}+1}^{T_{new}} \frac{E_{Cost}(t)\times 8760\times CF\times P_{New}}{(1+r)^t} \tag{6-1}$$

Where:

SV_{old} = Salvage Value of the removed turbine,

T_{new} = lifetime of the new wind turbine

T_{old} = remaining lifetime of old turbine

C_I = Capital Cost Incentives Available for the upgrade,

C_T = Transaction Costs

There is another option in areas where enough open space is available and where the wind is believed to be relatively constant over that open space. A new turbine could be installed in the vicinity of the old turbine, but far enough away so as to minimize wake losses between the turbines. However, this option will not be viable in populated areas with space constraints and where buildings will make the validity of wind measured at one location questionable in nearby locations.

However, in suburban locations where subsequent installations could be reliably assessed from an existing turbine's operation, new turbine installations are feasible. Incentives could be provided to early installers who make their operational data available to enable follow on installations. Such programs could potentially incentivize early adopters to commit to a wind turbine installation.

6.6 Advanced Assessment Techniques

It is clear from the analysis in Chapter 4 that nothing is quite as valuable as simply finding the best wind locations in urban areas. However, for the small wind turbine market, wind assessment and siting are a challenge for several reasons:

1. Assessment costs are a significant portion of total project cost.
2. Assessment adds cost for the buyer, and increases risk for the seller.
3. Tools for siting are geared toward large wind farms and require significant investment.

The current recommended wind site assessment for small wind turbines does not include any direct wind measurement. Instead, it relies on evaluating the potential wind turbine site and the prevailing winds in a particular area. Such assessments will suggest that turbines be installed 30 feet above surrounding obstacles in order to have clear access to the wind. Conservative wind estimates will be given that discount the prevailing wind speed. (Sagrillo 2010a, 2010b)

Software programs such as WAsP, Wind Atlas Analysis and Application Program, WindFarm from ReSoft Ltd., and WindPro from EMD International, have been developed to assist in the assessment and planning for large wind farms in rural areas. They have little practical use in urban areas and they are cost prohibitive to use on small projects.

Software for urban wind assessment is used to assist in the design of buildings to improve natural ventilation and pedestrian comfort. Extension of these software packages is being explored to siting wind turbines in urban environments.

At least two firms, Meteodyn and Wind Analytics, offer software products geared toward assessing the installation small wind turbines in urban environments. In addition to the announced launch of their software package, Wind Analytics offers a turnkey wind assessment of a proposed site for $2,500. This assessment is based on available data about the proposed turbine location. The assessment includes recommended turbine locations and estimates of energy output with estimated error of 12.5%. (Meteodyne 2010, Wind Analytics 2010)

Implementation of advanced siting techniques for small wind turbines is still in its early stages. Such techniques are relatively expensive compared to traditional site assessment for small wind, and the benefits of their use over traditional methods are not known. Further, it is not clear that urban wind turbines in general constitute a significant market for turbine development.

For this technology to be viable, its benefits need to be more clearly demonstrated. Until further data is available on how well this technology allows turbine siting to be improved, developers and installers will be reluctant to utilize it in their assessment process.

6.7 Challenges and Strategies for Turbine Manufacturers and Installers

Looking at the projected development of the wind turbine market, manufacturers should focus on reducing cost, increasing turbine choice, and maintaining or improving turbine reliability. It is important to establish these capabilities as the market grows. Technology improvements appear to offer limited returns in benefit to the industry. With over 200 firms competing in the small wind turbine space, companies with the best manufacturing capability, even if they lack the most advanced turbine technology, should be able to maintain their competitive advantage through partnerships, licensing deals, or acquisitions of new technology.

Creating a product line that includes turbine models in different size ranges allows the manufacturers to utilize their capabilities efficiently, and not take unnecessary risk on certain markets that may require specific turbine sizes. Also, having an upgrade path captures potential benefits that come from a flexible approach to selecting site capacity.

Finally, marketing and distribution efforts used by turbine installers should focus on identifying favorable target markets where electricity price, wind resource, and incentives are all favorable for development. Identifying the early adopters in these markets, and generating enough local sales in relatively close proximity can help reduce the assessment and installation costs associated with small wind turbines. Providing alternative financial models for installation, such as PPA agreements, can also help make small wind turbines more attractive to the market.

Chapter 7: Conclusions

This paper reviewed the wind industry and focused on the challenges and opportunities for developing small wind turbines in populated areas. The focus was on areas where noise, shadow flicker, public safety, and aesthetics will be potentially significant factors on the residents living nearby the small wind turbine.

A review of literature found that small wind turbines currently cost between $4 and $6 per watt of capacity, not including installation, when the wind turbine's power is rated at or around a wind speed of 12 m/s. After installation costs are considered, costs ranged from $5.83 per watt and above.

Several target applications for small wind turbines were analyzed including residential rooftops, the roof edges of commercial buildings, turbines mounted above the center of commercial buildings in both obstructed and obstructed environments. The range of typical wind speeds for these applications ranged from 3.5 m/s for residential rooftops, 4 m/s for roof edge applications, 5 m/s for obstructed rooftops, and 6 m/s for unobstructed rooftops. These values are estimates and represent applications would need to be satisfied if small wind turbine installations will reach a large scale adoption.

Customer's willingness to pay for small wind turbines to achieve grid parity with retail electricity pricing were found to range from under $1/Watt for residential rooftop applications, to $3.75/Watt for unobstructed rooftop applications where electricity prices are high and wind speeds are strong. The effects of government incentives are to increase the customer's willingness to pay to about $4.50/Watt. These costs require significant cost reduction compared to the costs of available small wind turbines.

An analysis of low wind speed turbines revealed that lowering the cut-in speed of small wind turbines did not result in significant benefits to an installation. However, lowering the rated speed of the turbine did result in improved performance, though this improvement needs to be achieved with reasonable cost. Increased turbine efficiency also resulted in higher target capital costs for turbines, though the effect was more pronounced for higher wind speed installations.

The cost structure of small wind turbines reveals opportunities for reducing costs in the siting and installation processes. Firms able to improve siting by identifying high locations with locally high wind speeds and able to lower installation costs, perhaps by installing multiple turbines at once stand to gain competitive advantage in the marketplace. Most firms in the industry currently rely on distributor/installer network to perform these two potential high value functions.

Other options for improving wind turbine installation were also considered. Using small wind turbines with emergency backup power systems did not result in significantly better economics for wind turbine installations. However, the prospect of upgrading installed wind turbines to larger models has potential advantages since siting costs are greatly reduced with the availability of historical data, and if existing foundation and tower infrastructure can be reused in the application.

In recognition of the value of identifying high local wind speeds, a brief review of advanced siting techniques was performed. Two companies offer CFD based wind assessment for the built environment. However, these services are relatively expensive, with a single assessment costing over $2,500. These may be appropriate for larger wind turbine installations, but will continue to be cost prohibitive for siting wind turbines under 5 kW in capacity.

Finally, a review of the small turbine market revealed relatively slow increase in the rate of technology development, with a moderate to potentially rapid increase in the size of the small turbine market. Such a market favors established firms with the resources to scale to the growth of the market. The establishment of standards within the industry helps to strengthen the position of established firms. Entrant firms need to increase the pace of technology development in order to gain in the market against the established firms.

References

Ampair. 2010. Company Website. http://www.ampair.com/ Accessed 25 April 2010.

AWEA. 2010. U.S. Wind Energy Projects-Massachusetts. http://www.awea.org/projects/Projects.aspx?s=Massachusetts Accessed 25 April 2010.

AWEA. 2009. AWEA Small Wind Turbine Global Market Study: Year Ending 2008. American Wind Energy Association. Washington, DC. http://www.awea.org/smallwind/pdf/09_AWEA_Small_Wind_Global_Market_Study.pdf. Accessed 15 March 2010.

AWEA. 2008. AWEA Small Wind Turbine Global Market Study 2008. American Wind Energy Association. Washington, DC. http://www.awea.org/smallwind/pdf/2008_AWEA_Small_Wind_Turbine_Global_Market_Study.pdf. Accessed 15 March 2010.

AWEA. 2007. AWEA Small Wind Turbine Global Market Study 2007. American Wind Energy Association. Washington, DC. http://www.awea.org/smallwind/documents/AWEASmallWindMarketStudy2007.pdf. Accessed 15 March 2010.

AWEA. 2005. "Home and Farm Wind Energy Systems: Reaching the Next Level" American Wind Energy Association. Washington, DC. http://www.awea.org/smallwind/documents/AWEA_SWT_Market_Study_6-05.pdf. Accessed 15 March 2010.

AWEA 2002. "The U.S. Small Wind Turbine Industry Roadmap. A 20-year industry plan for small wind turbine technology." American Wind Energy Association. Washington, DC. http://www.awea.org/smallwind/documents/31958.pdf.Accessed 15 March 2010.

Bailey, Brandon. 2010. "Adobe turns to the wind for power." San Jose Mercury News. http://www.mercurynews.com/breaking-news/ci_14191622?nclick_check=1. 19 January 2010. Accessed 23 March 2010.

Bergey Windpower. 2010. Company Website. http://www.bergey.com/ Accessed 25 April 2010.

Cace, Jadranka, Emil ter Horst, Katerina Syngellakis, Maite Niel, Patrick Clement, Renate Heppener, and Eric Peirano. 2007. "Urban Wind Turbines: Guidelines for small wind turbines in the built environment." http://www.urbanwind.net/pdf/SMALL_WIND_TURBINES_GUIDE_final.pdf. Accessed 18 March 2010.

Christensen., Clayton. 1992. "Exploring the Limits of the Technology S-Curve. Part II: Architectural Technologies" *Production and Operations Management.* Vol 1 Iss 4 pg 358-366.

DOE. 2008. "20% Wind Energy by 2030 Increaing Wind Energy's Contribution to U.S. Electricity Supply." US Department of Energy, Office of Energy Efficiency and Renewable Energy. DOE-GO-102008-2567. Washington, DC.

DSIRE. 2010. Database of State Incentives for Renewables and Efficiency. http://www.dsireusa.org/ Accessed 24 March 2010.

Dutton, A.G., J.A. Halliday, and M.J. Blanch. 2002. "The Feasibility of Building-Mounted/Integrated Wind Turbines (BUWTs): Achieving their potential for carbon emission reductions." UKERC Research Centre. http://ukerc.rl.ac.uk/cgi-bin/ercri4.pl?GChoose=gdets&GRN=2002-7-28-1-6&QString=SearchTerm=buw Accessed16 February 2010.

EIA. 2009a. Emissions of Greenhouse Gases in the US 2008-Carbon Dioxide Emissions. United States Department of Energy, Energy Information Administration. http://www.eia.doe.gov/oiaf/1605/flash/flash.html Accessed 24 March 2010

EIA. 2009b. State Electricity Profiles 2008. http://www.eia.doe.gov/cneaf/electricity/st_profiles/sep2008.pdf Accessed 1 May 2010

Encraft. 2009. "Warwick Wind Trials Final Report." http://www.warwickwindtrials.org.uk/resources/Warwick+Wind+Trials+Final+Report+.pdf. Accessed 24 March 2010.

Energy Saving Trust. 2009 "Location, Location, Location Domestic small-scale wind field trial report." London. http://www.energysavingtrust.org.uk/Global-Data/Publications/Location-location-location-The-Energy-Saving-Trust-s-field-trial-report-on-domestic-wind-turbines. Accessed 24 March 2010

Gans, Joshua S., and Scott Stern. 2003. "The Product market and the market for 'ideas': commercialization strategies for technology entrepreneurs." *Research Policy.* Vol. 31 pg 333-350.

George, K, and T. Schweizer. 2008. "Primer: The DOE Wind Energy Program's Approach to Calculating the Cost of Energy." NREL/SR-37653: Princeton Energy Resources International.

Geroski, Paul. 2000. "Models of Technology Diffusion." *Research Policy*, 2000, vol. 29, issue 4-5, pages 603-625

Gipe, Paul. 2009. *Wind Energy Basics: A guide to Home- and Community-Scale Wind Energy Systems* 2nd Ed. Chelsea Green. White River Junction, VT.

GWEC. 2010. *Global Wind 2009 Report.* Global Wind Energy Council. Brussels.

Heath, Malcom A., John D. Walshe, and Simon J. Watson. 2007. "Estimating the Potential Yield of Small Building-mounted Wind Turbines." *Wind Energy.* Volume 10, Issue 3. Pg. 271-287.

Home Energy. 2010. 2zCompany Website. http://www.home-energy.com/engels/mission.htm Accessed 1 May 2010.

IRS. 2009. "Energy Provisions of the American Recovery and Reinvestment Act of 2009" FS-2009-10. http://www.irs.gov/newsroom/article/0,,id=206871,00.html. Accessed 24 March 2010.

Khatri, Dilip. 2010. "Economics of Taller Wind Towers" Renewable Energy World North America. http://www.renewableenergyworld.com/rea/news/article/2010/02/economics-of-taller-wind-towers?cmpid=WNL-Friday-February19-2010. Accessed 12 March 2010.

Lazard. 2008. "Levelized Cost of Energy Analysis – Version 2.0". Presented at NARUC 2008 Summer Committee Meetings.

http://www.narucmeetings.org/Presentations/2008%20EMP%20Levelized%20Cost%20of%20Energy%20-%20Master%20June%202008%20(2).pdf. Accessed 15 March 2010

McDermott, Matthew. 2008. "The Energy Ball: Another Innovative Option in Home Wind Turbines" http://www.treehugger.com/files/2008/09/swedish-energy-ball-spherical-silent-home-wind-turbine.php Accessed 1 May 2010.

Mertens, Sanders. 2002. "Wind energy in urban areas: Concentrator effects for wind turbines close to buildings." *Refocus.* Issue 2, Volume 3.

Mertens, Sanders. 2005. *Wind Energy in the Built Environment*.

Meteodyne. 2010. Company web site. http://www.meteodyne.com/ Accessed 20 March 2010.

Moore, Geoffrey. 1991. *Crossing the Chasm.*Harper Business. New York.

Proven Energy. 2010. Company Website. http://www.provenenergy.co.uk/ Accessed 25 April 2010.

PVWatts. 2010. "PVWatts v. 1" http://rredc.nrel.gov/solar/calculators/PVWATTS/version1/ Accessed 2 May 2010.

Renewable Energy Trust. 2010. Massachusetts Commonwealth Wind Incentive Program. http://www.masstech.org/wind/micro_wind.html. Accessed 10 March 2010.

renewableUK. 2009. Small Wind Systems UK Market Report 2009. http://www.bwea.com/pdf/small/BWEA%20SWS%20UK%20Market%20Report%202009.pdf Accessed 23 April 2010

Rogers, Everett. 1995. *Diffusion of Innovations.* 4th ed. The Free Press. New York.

Sagrillo, Mick. 2010a. "Back to the Basics 7: Wind Resource Maps and Wind Site Assessments". *Windletter, The Monthly Newsletter of the American Wind Energy Association.* Vol 29. Iss. 3. March 2010.

Sagrillo, Mick. 2010b. "Back to the Basics 8: Wind Site Assessments". *Windletter, The Monthly Newsletter of the American Wind Energy Association.* Vol 29. Iss. 4. April 2010.

Sharman, David. 2010. "Getting Real About Small Wind." *Renewable Energy Focus*. Volume 11 Issue 1. Pg. 30-32.

Shaw, Shawn. 2008. "Progress Report on Small Wind Energy Development Projects Receiving Funds form the Massachusetts Technology Collaborative (MTC)" http://www.masstech.org/IS/sm_renew/Small%20Wind%20Progress%20Report%20061208.pdf Accessed 12 April 2010.

Southwest Windpower. Company Website. http://www.skystreamenergy.com/ Accessed 25 April 2010.

Southwest Windpower. "Skystream 3.7 Technical Specifications." http://www.windenergy.com/documents/spec_sheets/3-CMLT-1338-01_Skystream_spec.pdf.Accessed 24 March 2010

Stankovic, Sinisa, Neil Campbell, and Alan Harries. 2009. *Urban Wind Energy.* Earthscan. Sterling, VA.

Suarez, Fernando, and Gianvito Lanzolla. 2005. Half-Truth of First-Mover Advantage. *Harvard Business Review*. April 2005.

SWAY. 2010. Company Website. http://www.sway.no/?page=165 Accessed 1 May 2010.

Tester, Jefferson W., Elisabeth M. Drake, Michael W. Golay, Michael J. Driscoll, and William A. Peters. 2005. *Sustainable Energy, Choosing Among Options*. The MIT Press. Cambridge, MA.

US Census Bureau. 2009 "Population Density for Counties and Puerto Rico Municipios: July 1 2009" http://www.census.gov/popest/gallery/maps/County-Density-09.html . Accessed 22 March 2010.

VentureWire. 2010. "Windspire Energy Keeps Its Series C Party Private" https://www.fis.dowjones.com/article.aspx?ProductIDFromApplication=32&aid=DJFVW00020100419e64k0018h&r=Rss&s=DJFVW Accessed 24 April 2010

Viterna, Larry A., and Daniel F. Ancona III. 2009 "Modern Wind Turbine Systems" Chapter 4 in *Wind Turbine Technology.* David Spera Ed. ASME Press.

Wind Analytics. 2010. Company Website. http://www.windanalytics.com/ Accessed 25 April 2010

Wind Powering America. 2010. US Department of Energy Office of Energy Efficiency and Renewable Energy. http://www.windpoweringamerica.gov/wind_maps.asp Accessed 25 April 2010.

Windspire Energy. 2010. Company Website. http://windspireenergy.com/ Accessed 25 April 2010.

WindTronics. 2010. Company Website. http://www.earthtronics.com/honeywell.aspx Accessed 1 May 2010.

Wiser, Ryan, and Mark Bolinger. 2008. "Annual Report on U.S. Wind Power Installation, Cost, and Performance Trends: 2007" US Department of Energy DOE/GO-102008-2590

Wizelius, Tore. 2007. *Developing Wind Power Projects: Theory and Practice.* Eathscan. Sterling, VA.

Wright, Alan D. 2009 "Wind Turbine Control Systems" Chapter 14 in *Wind Turbine Technology.* David Spera Ed. ASME Press.